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Advancing the Fundamental Understanding of Fission

LDRD 20120077DR Review

Morgan White, Fredrik Tovesson & Arnie Sierk,

for the SPIDER Collaboration

February 4, 2014

3:00 to 5:00 PM

Pinon Conference Room (53/31/201)

Abstract

The following slides were presented as part of the LDRD 20120077DR Progress Appraisal Review held Tuesday, February 4, 2014. This is part of an ongoing project assessment the previous of which was documented in LA-UR-13-21182. This presentation documents the progress made against the goals agreed to as part of the 2013 review.

The SPIDER Collaboration

- **Los Alamos National Laboratory (LANL)**
  Charles Arnold, Todd Bredeweg, Tom Burr, Matt Devlin, Mac Fowler, Marian Jandel, Justin Jorgenson, Alexander Laptev, John Lestone, Paul Lisowski, Rhiannon Meharchand, Krista Meierbachtol, Peter Moller, Ron Nelson, John O'Donnell, Brent Perdue, Arnie Sierk, Fredrik Tovesson, Dave Vieira, Morgan White

- **University of New Mexico (UNM)**
  Adam Hecht, Rick Blakeley, Erin Dughie, Drew Mader

- **Colorado School of Mines (CSM)**
  Uwe Greife, Bill Moore, Dan Shields

- **Lawrence Livermore National Laboratory (LLNL)**
  Lucas Snyder

- **Lawrence Berkeley Laboratory (LBL)**
  Jorgen Randrup

Agenda

- Overview – M. White
- Experiment – F. Tovesson
- Theory – A. Sierk
- Summary – M. White
- Discussion – All

Proposed Innovation And Anticipated Results

Original Proposal

- Measure fission-fragment yields as a function of (Ei,Z,A,TKE)
  - These data are a "holy grail" for fission science; much will flow from them
  - Good thermal data exist but the incident energy (Ei) dependence remains unknown
  - Our measurements will reach 2-5% accuracy from 0.01 eV to 20 MeV
- Develop theory in order to evaluate fission yield data
  - Based on the LANL nuclear potential-energy model
    - Demonstrated track record for nuclear mass, beta decay, mean fission splits,…
  - Langevin equations for inertial and dissipation effects will be used to model the dynamic evolution of fission across the potential-energy surface
  - Experimental data will be used to probe the initial conditions and underlying parameters and "fine-tune" their settings allowing extrapolation to other regimes
- Provide an evaluation of the Pu239 fission yields
  - Evaluation blends the best of experiment and theory to provide complete data
  - Provide a definitive answer regarding the energy-dependence of Nd147 yield

Where Do We Go From Here
No Plan Survives The First Skirmish

Last Year

- Measure fission-fragment yields as a function of (Ei,Z,A,TKE)
  - Use existing prototypes to continue development of final components
  - Build and populate as much of final detector as possible
  - Take measurements proving the utility and benefit of a future systematic campaign
- Develop theory in order to evaluate fission yield data
  - Continue development of advanced theory
  - Use existing tools to develop evaluations based on new measurements
- Provide an evaluation of the Pu239 fission yields
  - Provide a definitive answer regarding the energy-dependence of Nd147 yield

Agenda

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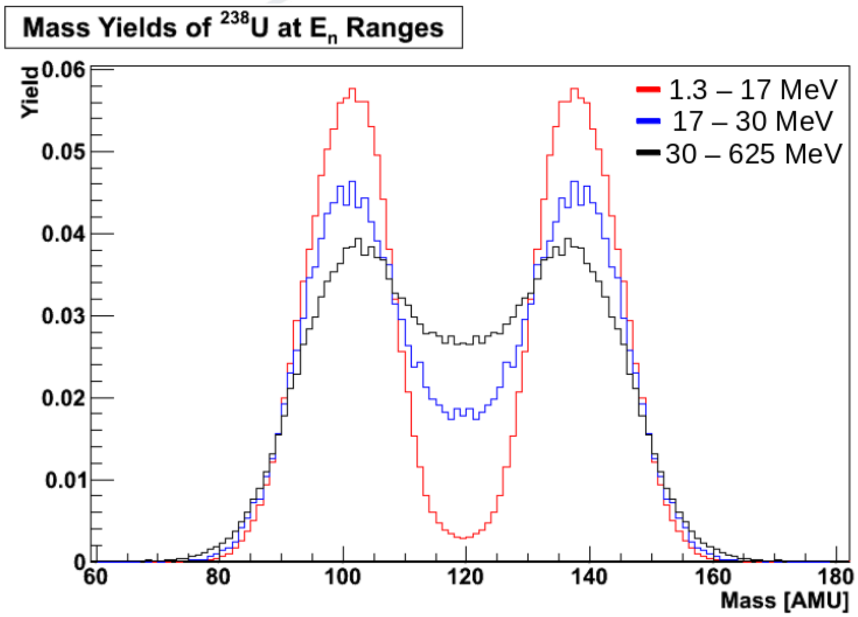
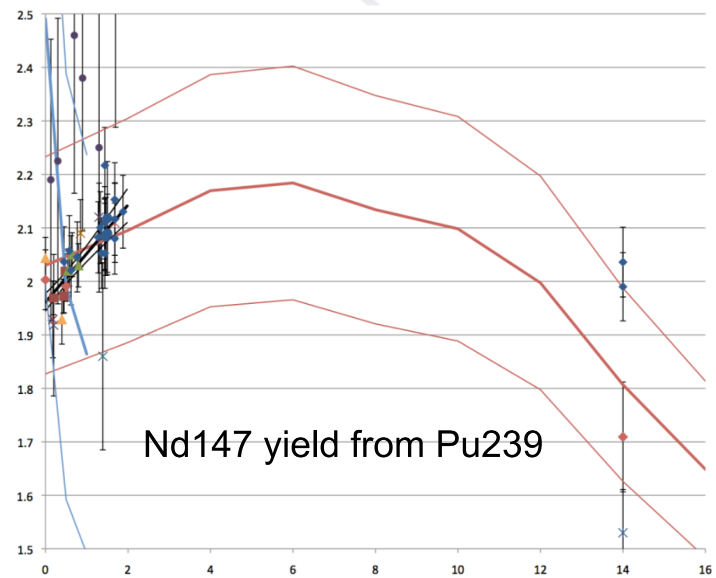
Goal Is To Measure Energy Dependence Of Fission Fragment Yields

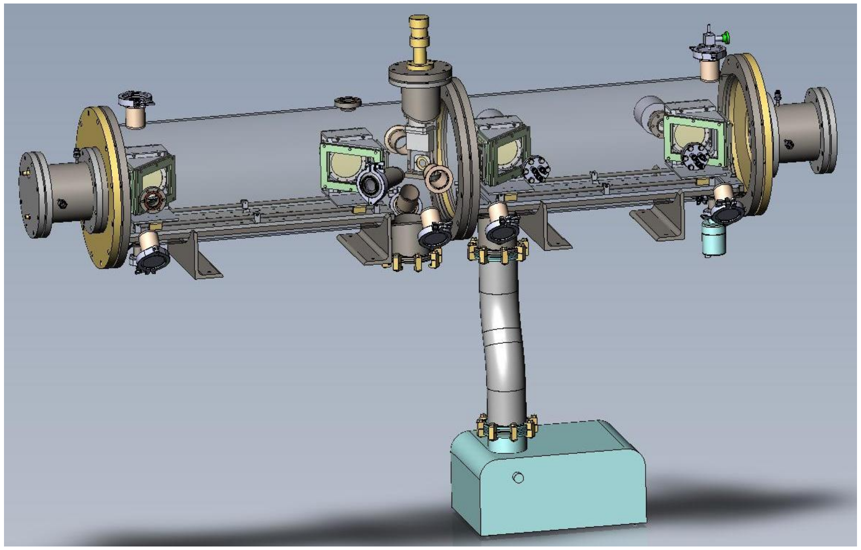




- Fission mass distributions are sensitive to incident neutron energy
- Yields of specific fission products (such as Nd-147) are important for applications and the energy dependence of these yields is not well known
- Accurate distributions of mass, charge, and energy – and their correlations – are the basis of advanced fission models

SPectrometer for Ion Determination in fission Research (SPIDER)

- Based on the 2E-2V method
- Time-of-flight
  - MCP-based time pick-offs with electrostatic mirrors
  - 150ps (FWHM) resolution per detector
- Energy and nuclear charge measurement
  - Ionization chambers
  - 0.5-1.0% energy resolution for fission fragments
  - dE/E measurement to determine nuclear charge
- Multiple detectors to increase efficiency
- Position resolution to reduce flight path length flight path uncertainty



Objectives

- Develop high resolution fragment spectrometer
  - 200 ps resolution time-of-flight assembly (150 ps per detector)
  - 0.5% energy resolution
  - Low energy loss chamber window
  - Instrument dual-arm spectrometer
- Measure thermal and spontaneous fission yields
  - U-235 and Pu-239
  - Cf-252(sf)
- Build large detector array
- Measure fission yields for fast neutrons
  - U-235 and Pu-239

Current Status

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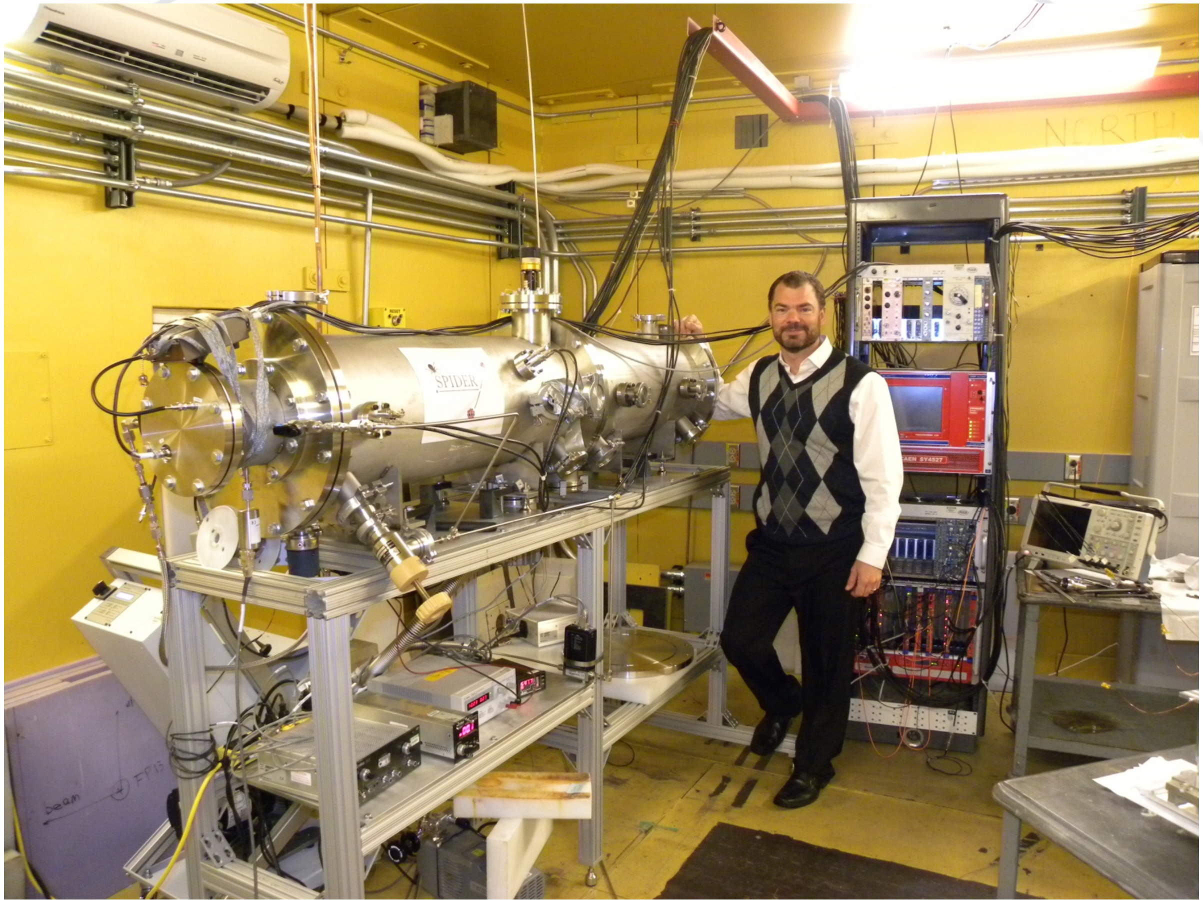
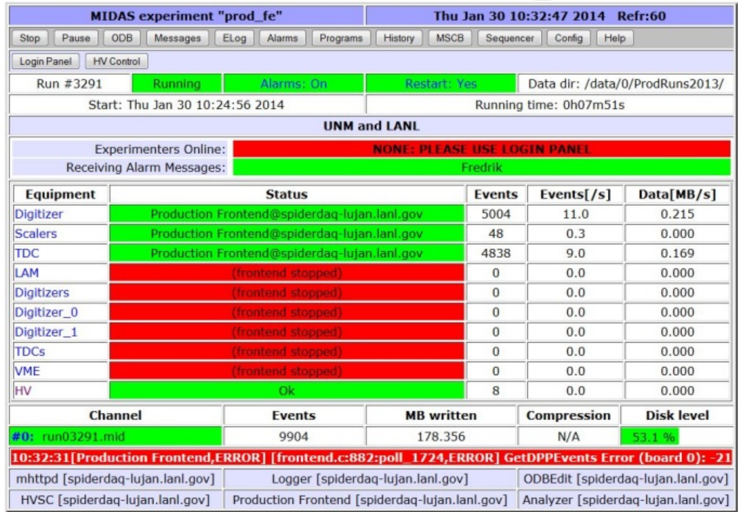
- Developed and tested TOF spectrometer and ionization chamber
- Commissioned single arm detector
- Measured U-235(n_{th}, f) and Cf-252 (sf) yields
- Assembled dual-arm spectrometer
- Optimization in progress
  - Current resolution is 2-3 AMU
  - Limited by current windows (Mylar)
  - Working in scaling up SiN windows – will get us to 1 AMU resolution
- Conceptual designs for scaled up spectrometer
  - 9 dual-arm design is ~90% complete
  - 3-6 dual-arm options are under consideration

SPIDER is Installed at Lujan Center FP12 and Taking Data!



SPIDER collaboration has developed state-of-the-art capabilities that will be a key part of future advanced measurements.

Data Acquisition System



MIDAS experiment "prod_fe" | Thu Jan 30 10:32:47 2014 Refr:60

Stop | Pause | ODB | Messages | ELog | Alarms | Programs | History | MSCB | Sequencer | Config | Help

Login Panel | HV Control

Run #3291 | Running | Alarms: On | Restart: Yes | Data dir: /data/0/ProdRuns2013/

Start: Thu Jan 30 10:24:56 2014 | Running time: 0h07m51s

UNM and LANL

Experimenters Online: NONE: PLEASE USE LOGIN PANEL

Receiving Alarm Messages: Fredrik

Equipment	Status	Events	Events[/s]	Data[MB/s]
Digitizer	Production Frontend@spiderdaq-lujan.lanl.gov	5004	11.0	0.215
Scalers	Production Frontend@spiderdaq-lujan.lanl.gov	48	0.3	0.000
TDC	Production Frontend@spiderdaq-lujan.lanl.gov	4838	9.0	0.169
LAM	(frontend stopped)	0	0.0	0.000
Digitizers	(frontend stopped)	0	0.0	0.000
Digitizer_0	(frontend stopped)	0	0.0	0.000
Digitizer_1	(frontend stopped)	0	0.0	0.000
TDCs	(frontend stopped)	0	0.0	0.000
VME	(frontend stopped)	0	0.0	0.000
HV	Ok	8	0.0	0.000

Channel	Events	MB written	Compression	Disk level
#0: run03291.mid	9904	178.356	N/A	53.1 %

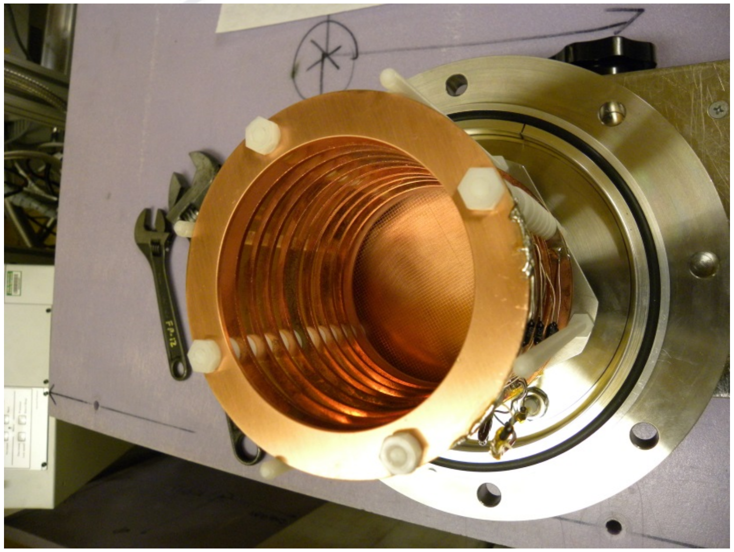
10:32:31[Production Frontend,ERROR] [frontend.c:882:poll_1724,ERROR] GetDPPEvents Error (board 0): -21

mhttpd [spiderdaq-lujan.lanl.gov]	Logger [spiderdaq-lujan.lanl.gov]	ODBEdit [spiderdaq-lujan.lanl.gov]
HVSC [spiderdaq-lujan.lanl.gov]	Production Frontend [spiderdaq-lujan.lanl.gov]	Analyzer [spiderdaq-lujan.lanl.gov]

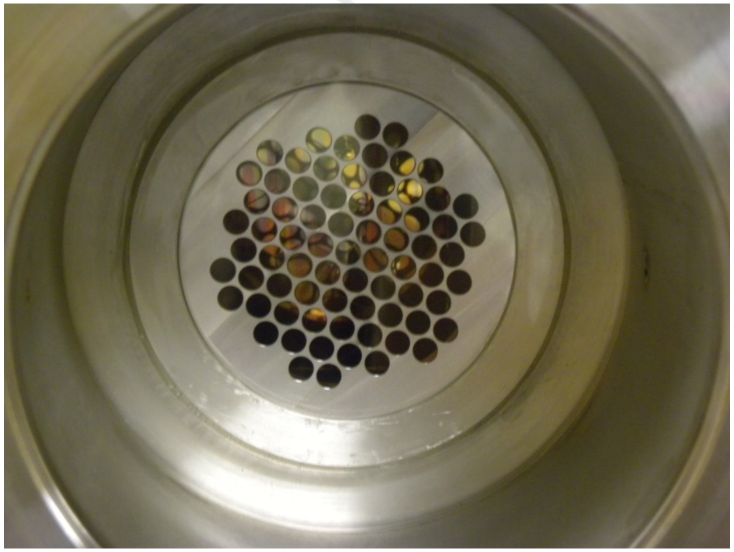
- Three crates of electronics: HV, NIM, VME
- Will support up to 10 arm pairs without adding more crates
- Slow control of HV, vacuum pump and gas handling
  - Monitoring
  - Alarms

Crossing into the digital age.

Ionization Chamber



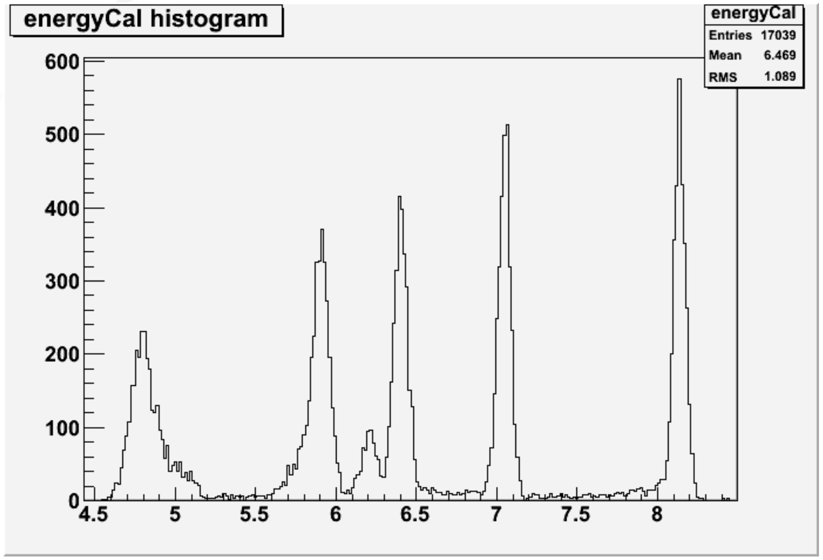
Axial chamber design

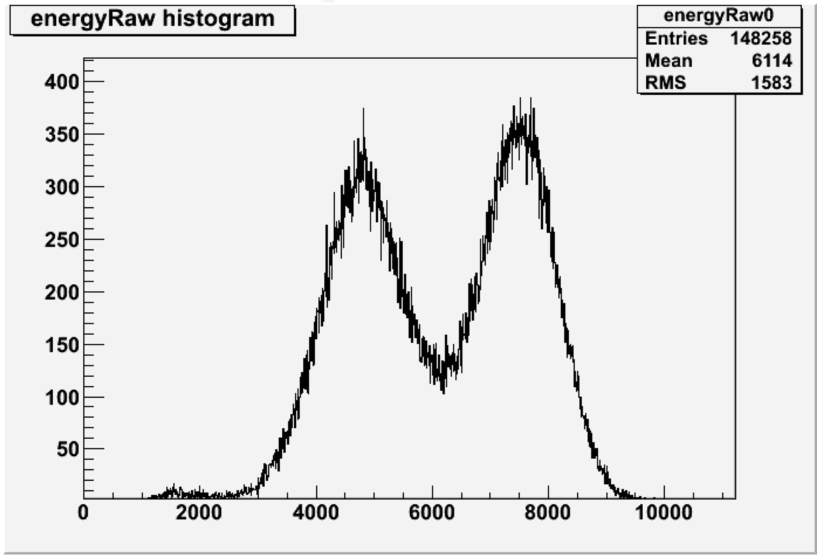


Mylar window on support mesh

Los Alamos has a long history of making state-of-the-art ionization chambers measurements, particularly for fission.

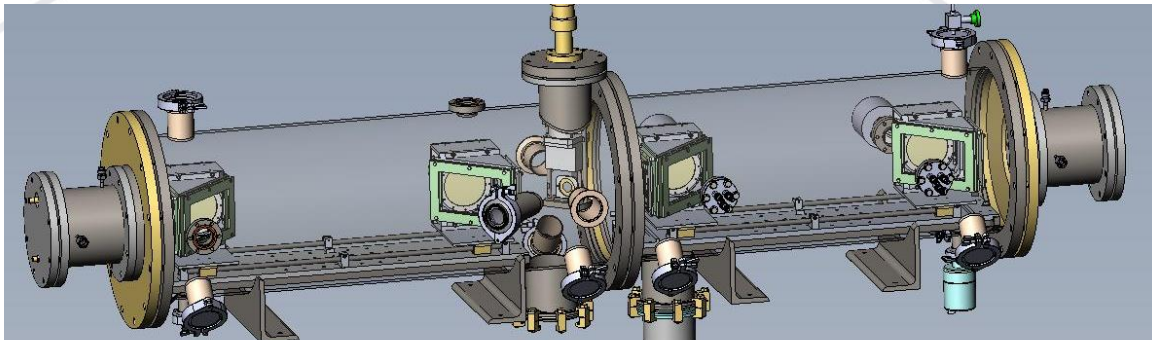
Ionization Chamber Performance

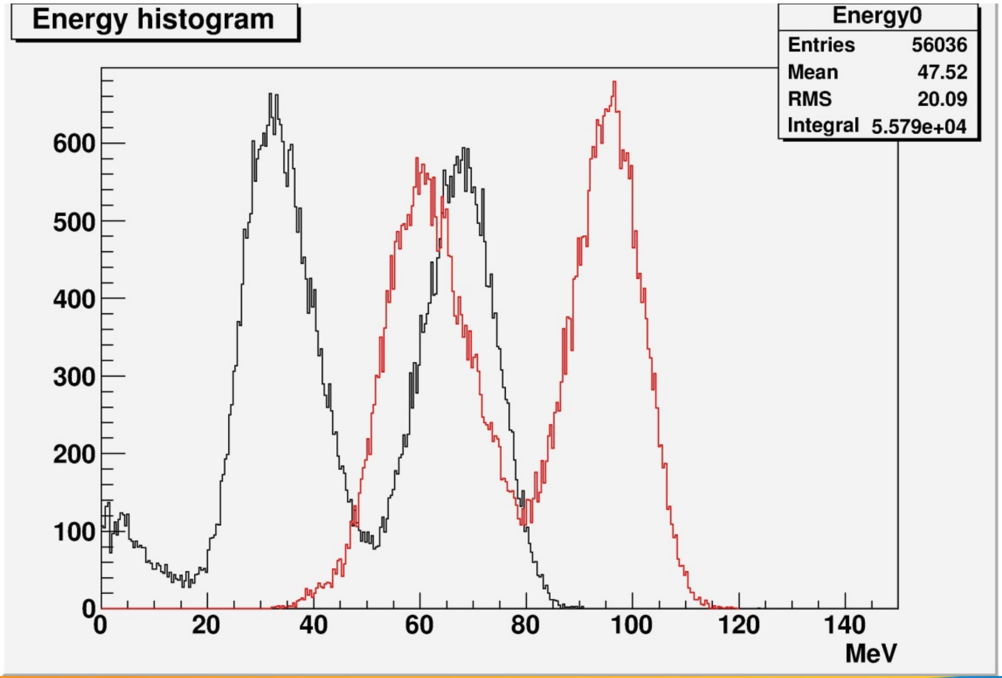




- Alpha particle spectrum shows that energy resolution is optimized
- 1% resolution for alphas translates to 0.5% for fission fragments
- Calibration spectrum with Cf-252(sf)

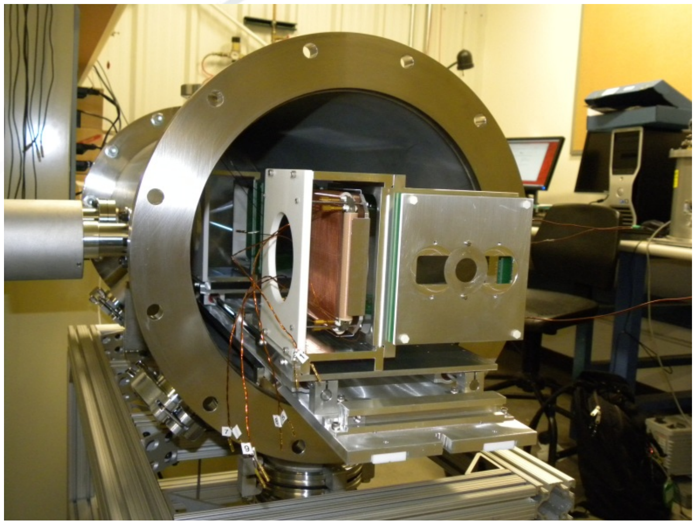
Ionization Chamber Energy Resolution

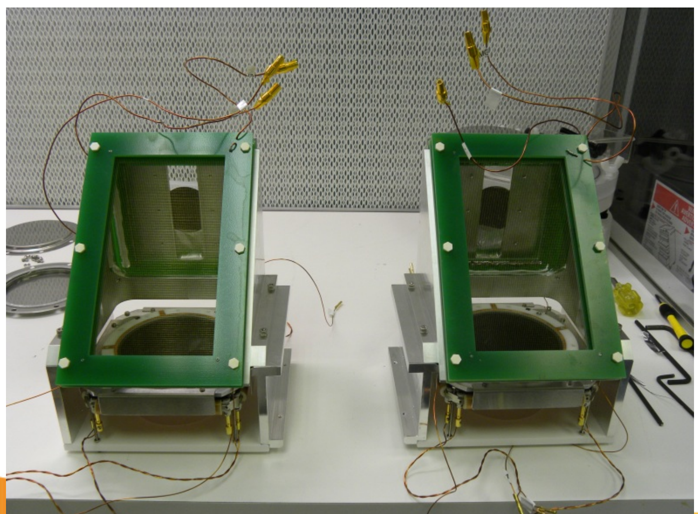


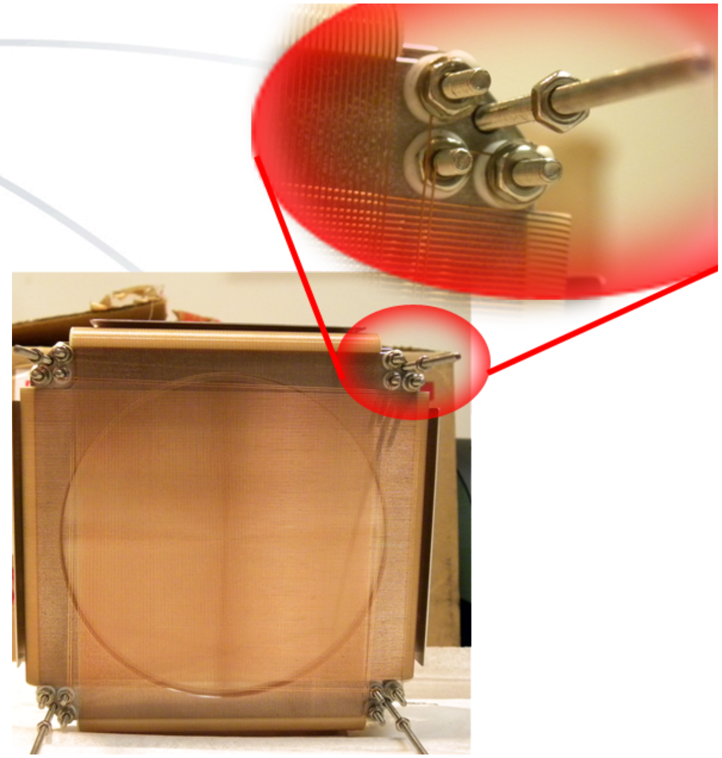


- With current window the energy loss is about 30%
- The energy loss is corrected using velocity measurements

Time Pick-Off Detectors

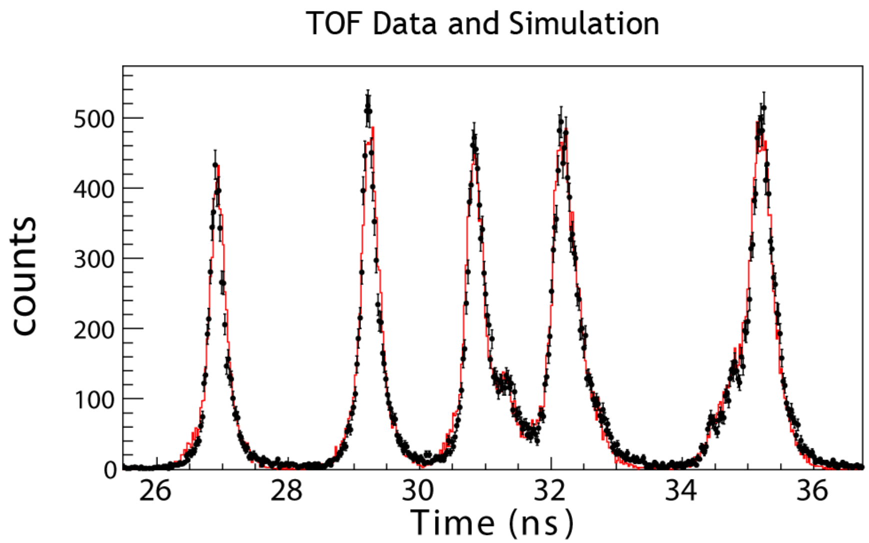






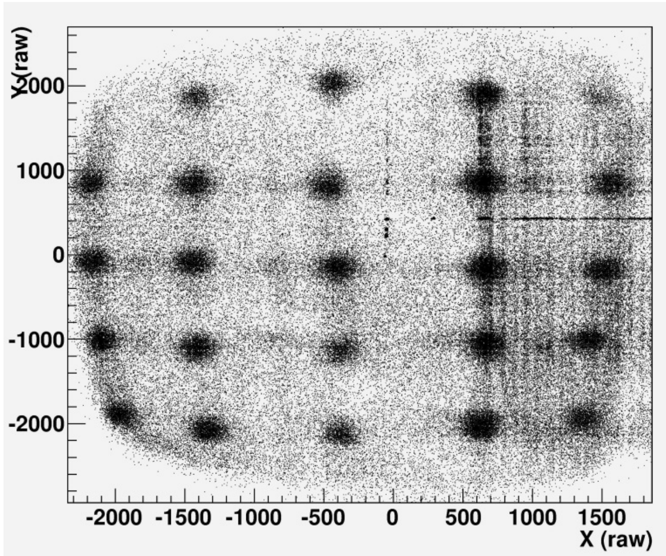
Development of large area sub-nanosecond timing detectors will enable us to make the measurements of interest today, and in the future.

Timing Detector Performance

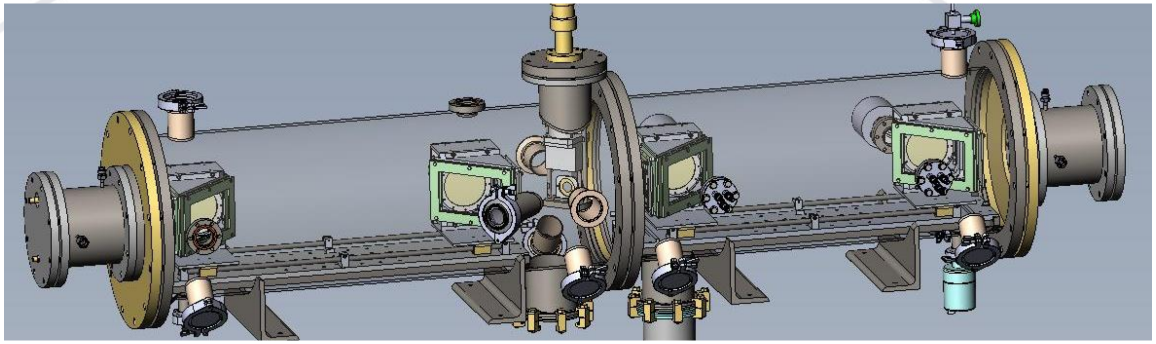


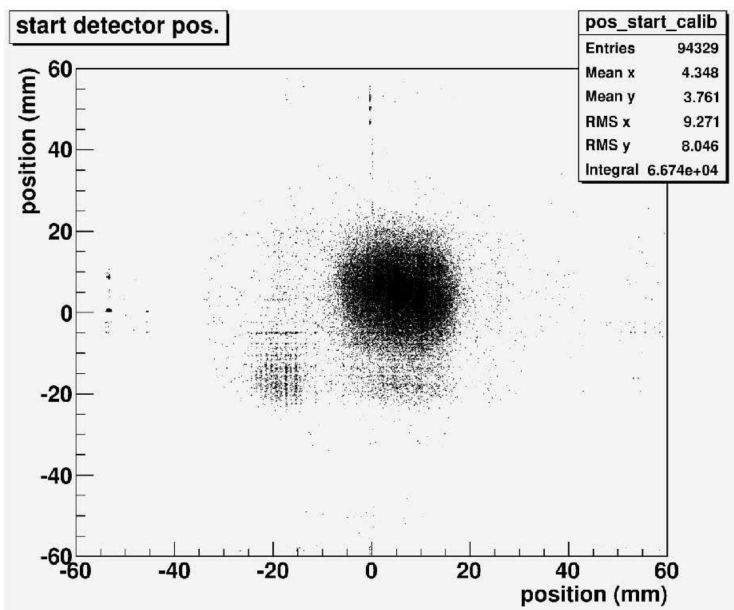
Temporal resolution for detector pair Δt=200ps (FWHM)

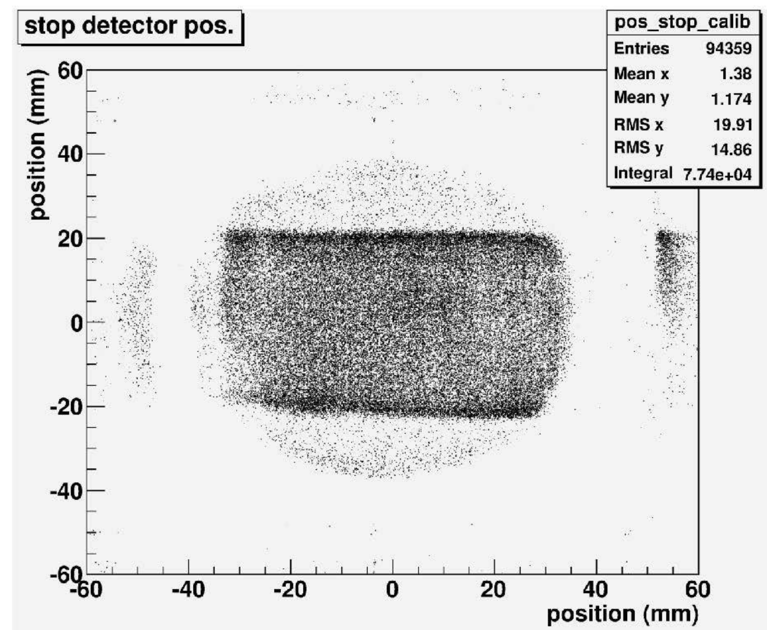
Spatial resolution 2 mm (FWHM)



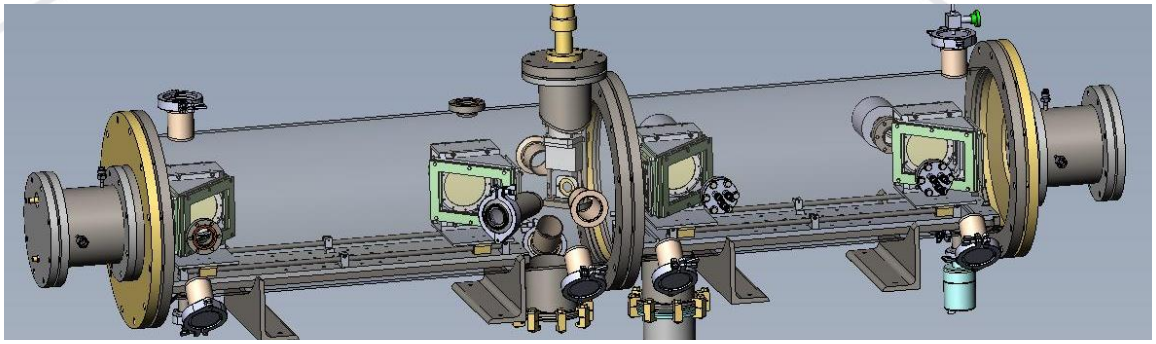
Fragment Trajectories

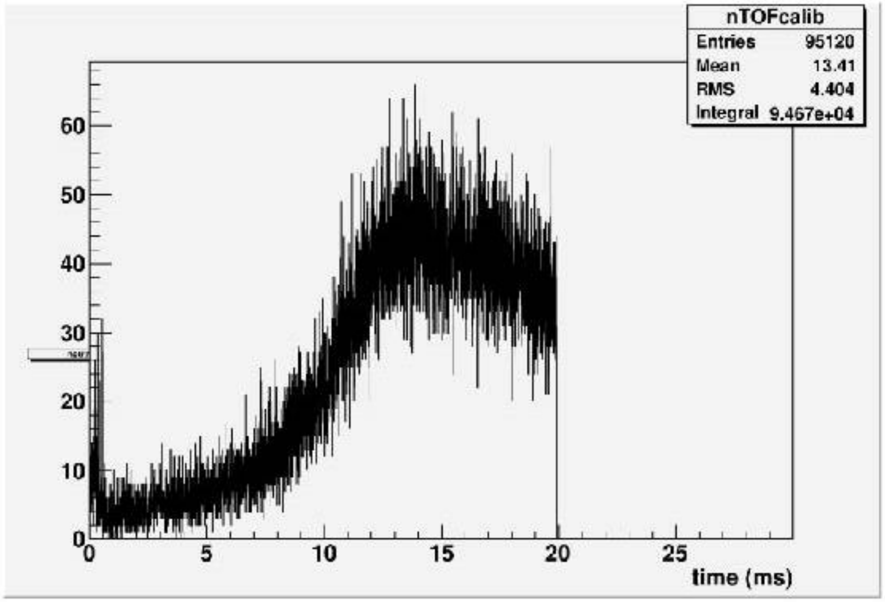


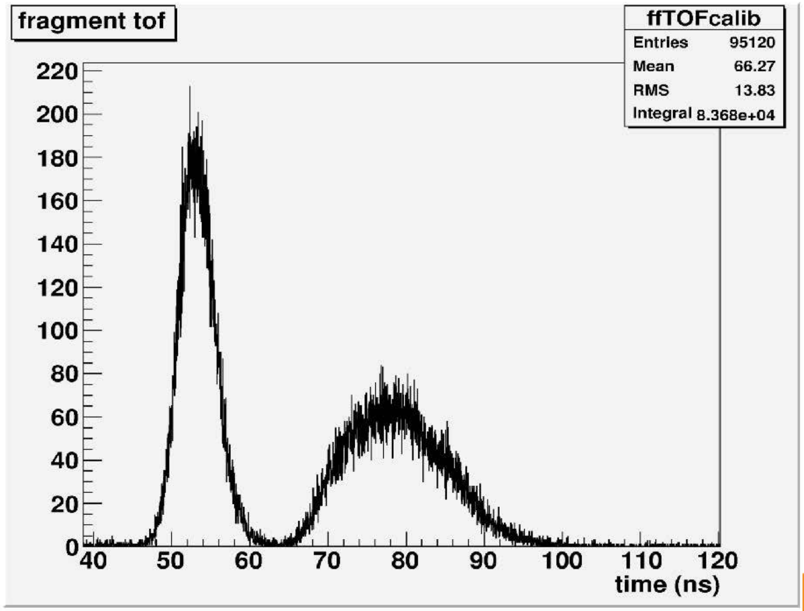




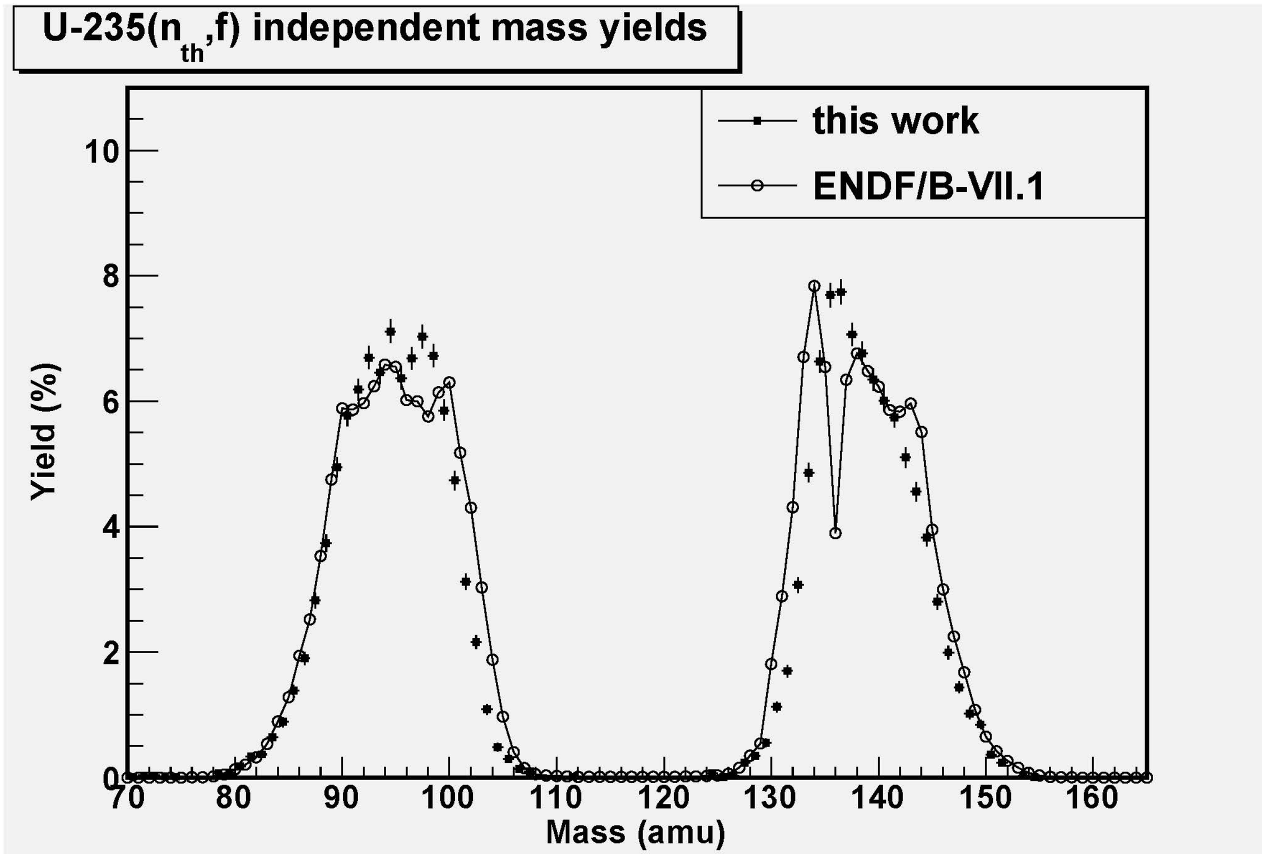
Neutron and Fragment Time-Of-Flight





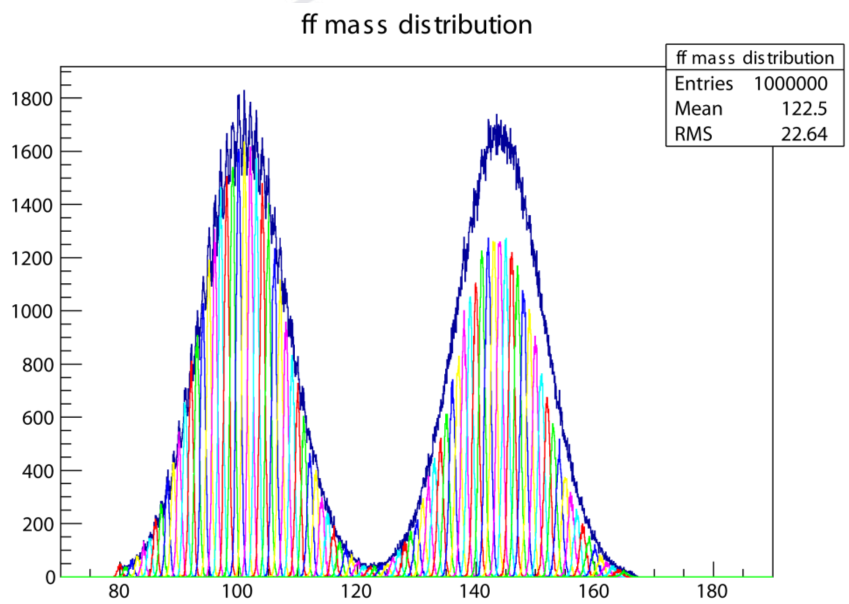


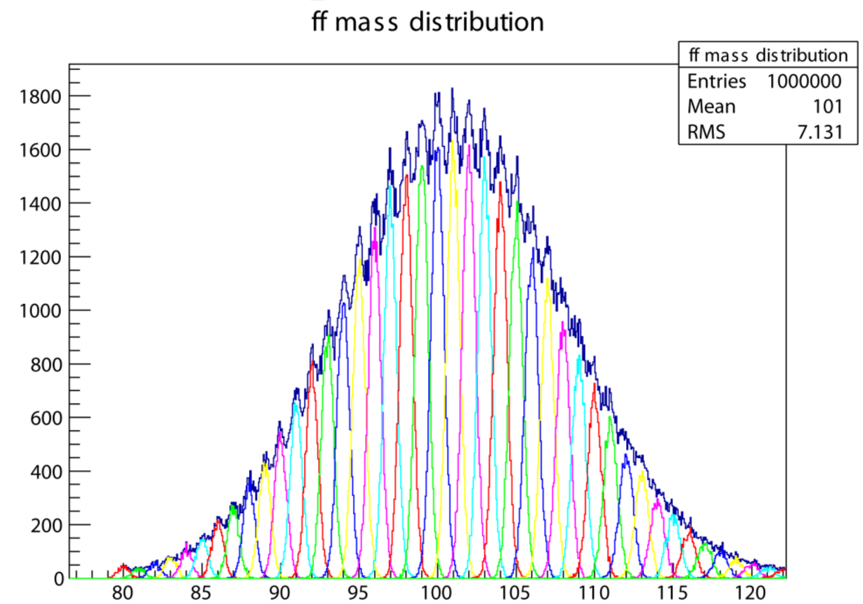
Preliminary Mass Yield!



Difficulties with the 2E,2V method arise from mechanical issues; the data is clean, almost background free.

Simulated Mass Yield Expectations For Final Configuration





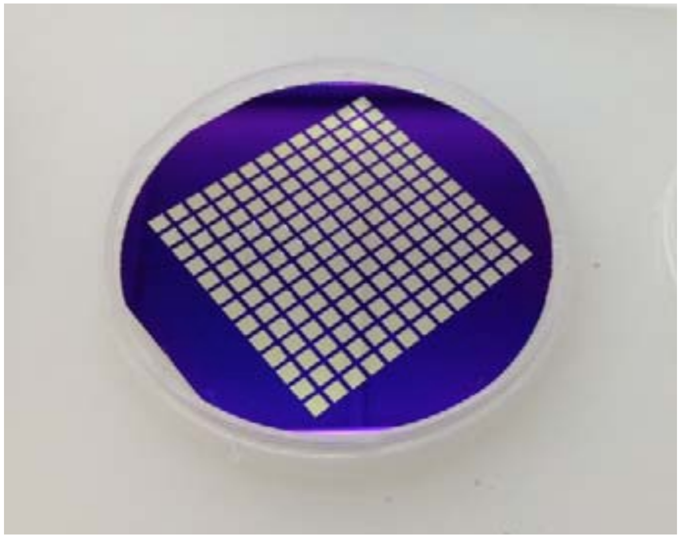
- The mass resolution was simulated based on experimentally determined temporal resolution and expected energy resolution
- With 60 cm flight path ~1 amu resolution for light fragments are expected

SiN Windows
A Path Towards 1 AMU

- We have tested small windows successfully
- Challenge is in scaling up

- First failure mode: structural material broke
- First problem solved by using additional support structure

- Second failure mode: mounting procedure causes individual windows to break
- Second problem is being addressed by changing the mounting mechanism

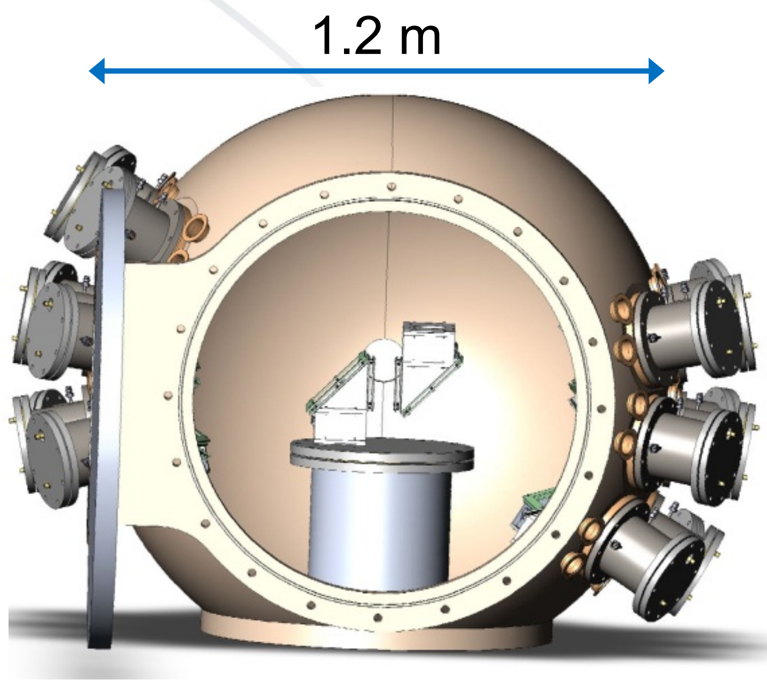


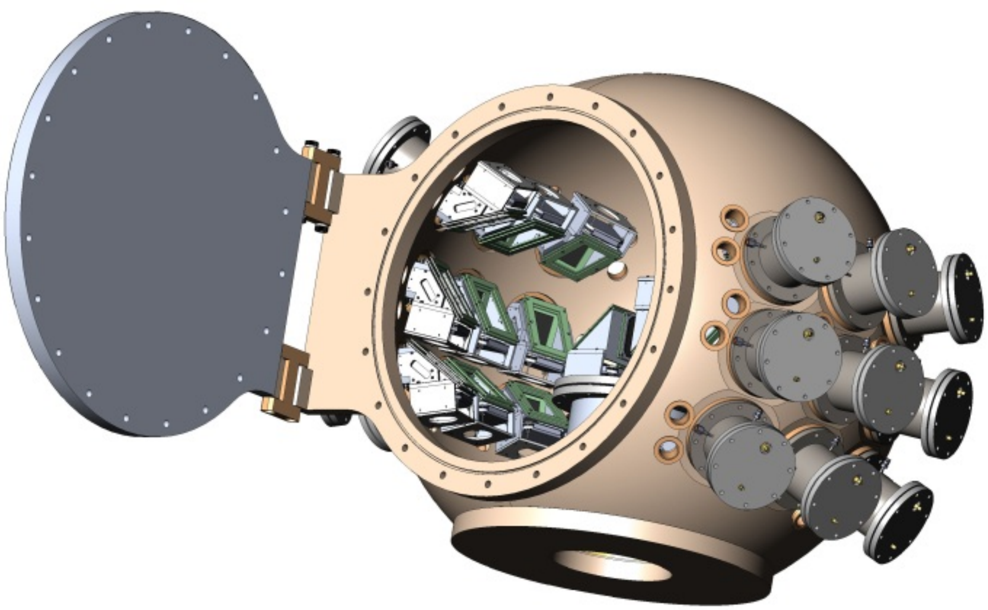
Expectations For FY2014

- Installation of SiN windows
- Dual-arm commissioning
  - High resolution Cf-252 data will be collected
  - This data will be used for Dan Shields's PhD thesis
- Ionization chamber calibration
  - UC Berkeley cocktail beam
  - In discussion on capabilities and timelines
- Finalize design on scaled up instrument

Beyond The 20120077DR…

- "Go big" option:
  spherical chamber with 9 x 2 arms
- Intermediate option:
  Cylindrical chamber with 3-6 arm pairs in one plane





Summary

- Dual-arm spectrometer has been commissioned
  - Neutron induced fission measurements taken using thermal/ epithermal beam on U235 at Lujan Center
- Capability to make high-precision measurements of fission mass distributions has been shown
- Optimization to reach 1 AMU resolution is in progress
  - Challenges with SiN windows are mechanical, not research
- Next steps is to scale up the instrument for fast neutron experiments

Agenda

- Overview – M. White
- Experiment – F. Tovesson
- Theory – A. Sierk
- Summary – M. White
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Building Upon A Rich Historical Legacy

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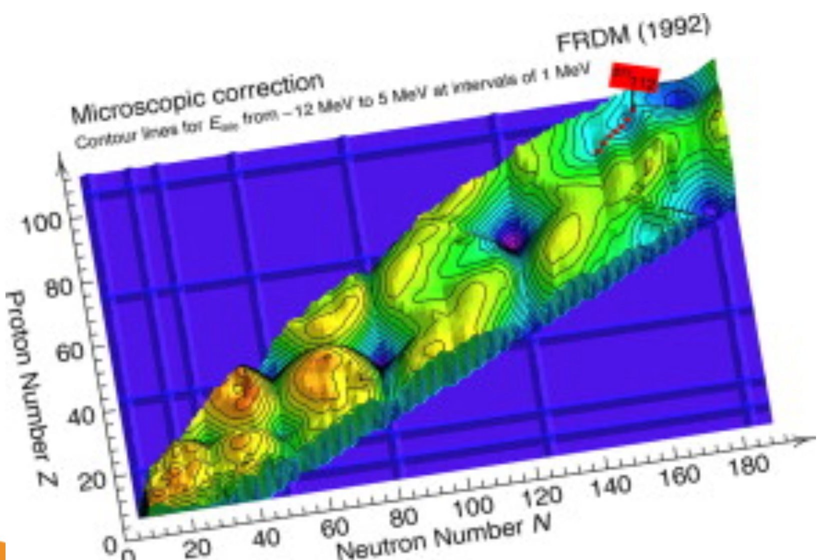
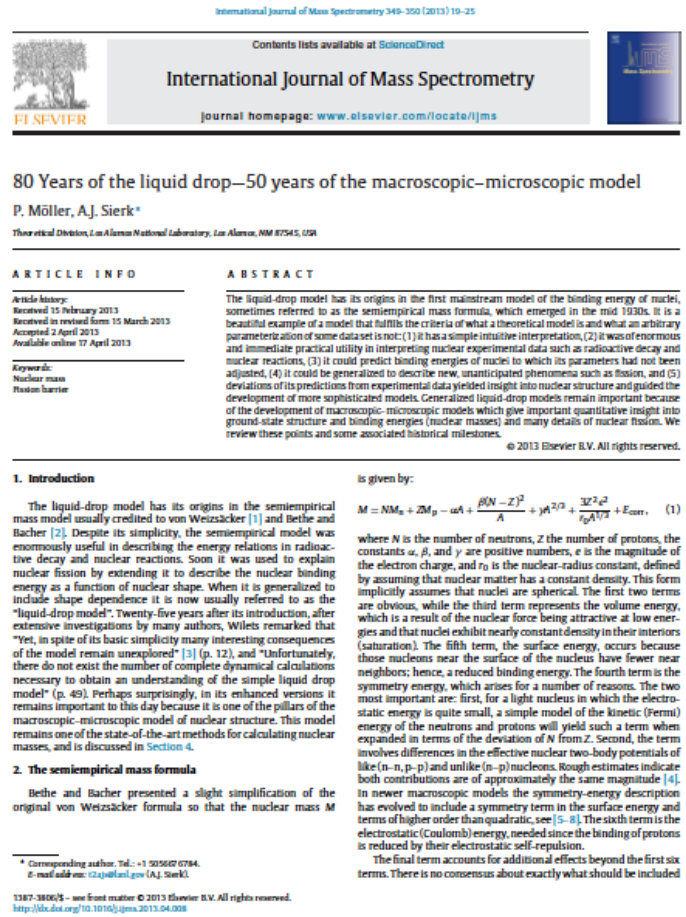
Decades of pioneering research calculating nuclear potential energies and dynamical models has matured to the point that we believe a quantitatively predictive fission-fragment model is possible.



2013 Review Article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80 Years of the liquid drop—50 years of the macroscopic–microscopic model

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ABSTRACT

The liquid-drop model has its origins in the first mainstream model of the binding energy of nuclei, sometimes referred to as the semiempirical mass formula, which emerged in the mid 1930s. It is a beautiful example of a model that fulfills the criteria of what a theoretical model is and what an arbitrary parameterization of some data set is not: (1) it has a simple intuitive interpretation, (2) it was of enormous and immediate practical utility in interpreting nuclear experimental data such as radioactive decay and nuclear reactions, (3) it could predict binding energies of nuclei to which its parameters had not been adjusted, (4) it could be generalized to describe new, unanticipated phenomena such as fission, and (5) deviations of its predictions from experimental data yielded insight into nuclear structure and guided the development of more sophisticated models. Generalized liquid-drop models remain important because of the development of macroscopic–microscopic models which give important quantitative insight into ground-state structure and binding energies (nuclear masses) and many details of nuclear fission. We review these points and some associated historical milestones.

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1. Introduction

The liquid-drop model has its origins in the semiempirical mass model usually credited to von Weizsäcker [1] and Bethe and Bacher [2]. Despite its simplicity, the semiempirical model was enormously useful in describing the energy relations in radioactive decay and nuclear reactions. Soon it was used to explain nuclear fission by extending it to describe the nuclear binding energy as a function of nuclear shape. When it is generalized to include shape dependence it is now usually referred to as the "liquid-drop model". Twenty-five years after its introduction, after extensive investigations by many authors, Wilets remarked that "Yet, in spite of its basic simplicity many interesting consequences of the model remain unexplored" [3] (p. 12), and "Unfortunately, there do not exist the number of complete dynamical calculations necessary to obtain an understanding of the simple liquid drop model" (p. 49). Perhaps surprisingly, in its enhanced versions it remains important to this day because it is one of the pillars of the macroscopic–microscopic model of nuclear structure. This model remains one of the state-of-the-art methods for calculating nuclear masses, and is discussed in Section 4.

2. The semiempirical mass formula

Bethe and Bacher presented a slight simplification of the original von Weizsäcker formula so that the nuclear mass M is given by:

$$M = NM_n + ZM_p - \alpha A + \frac{\beta(N-Z)^2}{A} + \gamma A^{2/3} + \frac{3Z^2e^2}{r_0 A^{1/3}} + E_{\rm corr}, \quad (1)$$

where N is the number of neutrons, Z the number of protons, the constants α, β, and γ are positive numbers, e is the magnitude of the electron charge, and r_0 is the nuclear-radius constant, defined by assuming that nuclear matter has a constant density. This form implicitly assumes that nuclei are spherical. The first two terms are obvious, while the third term represents the volume energy, which is a result of the nuclear force being attractive at low energies and that nuclei exhibit nearly constant density in their interiors (saturation). The fifth term, the surface energy, occurs because those nucleons near the surface of the nucleus have fewer near neighbors; hence, a reduced binding energy. The fourth term is the symmetry energy, which arises for a number of reasons. The two most important are: first, for a light nucleus in which the electrostatic energy is quite small, a simple model of the kinetic (Fermi) energy of the neutrons and protons will yield such a term when expanded in terms of the deviation of N from Z. Second, the term involves differences in the effective nuclear two-body potentials of like (n–n, p–p) and unlike (n–p) nucleons. Rough estimates indicate both contributions are of approximately the same magnitude [4]. In newer macroscopic models the symmetry-energy description has evolved to include a symmetry term in the surface energy and terms of higher order than quadratic, see [5–8]. The sixth term is the electrostatic (Coulomb) energy, needed since the binding of protons is reduced by their electrostatic self-repulsion.

The final term accounts for additional effects beyond the first six terms. There is no consensus about exactly what should be included

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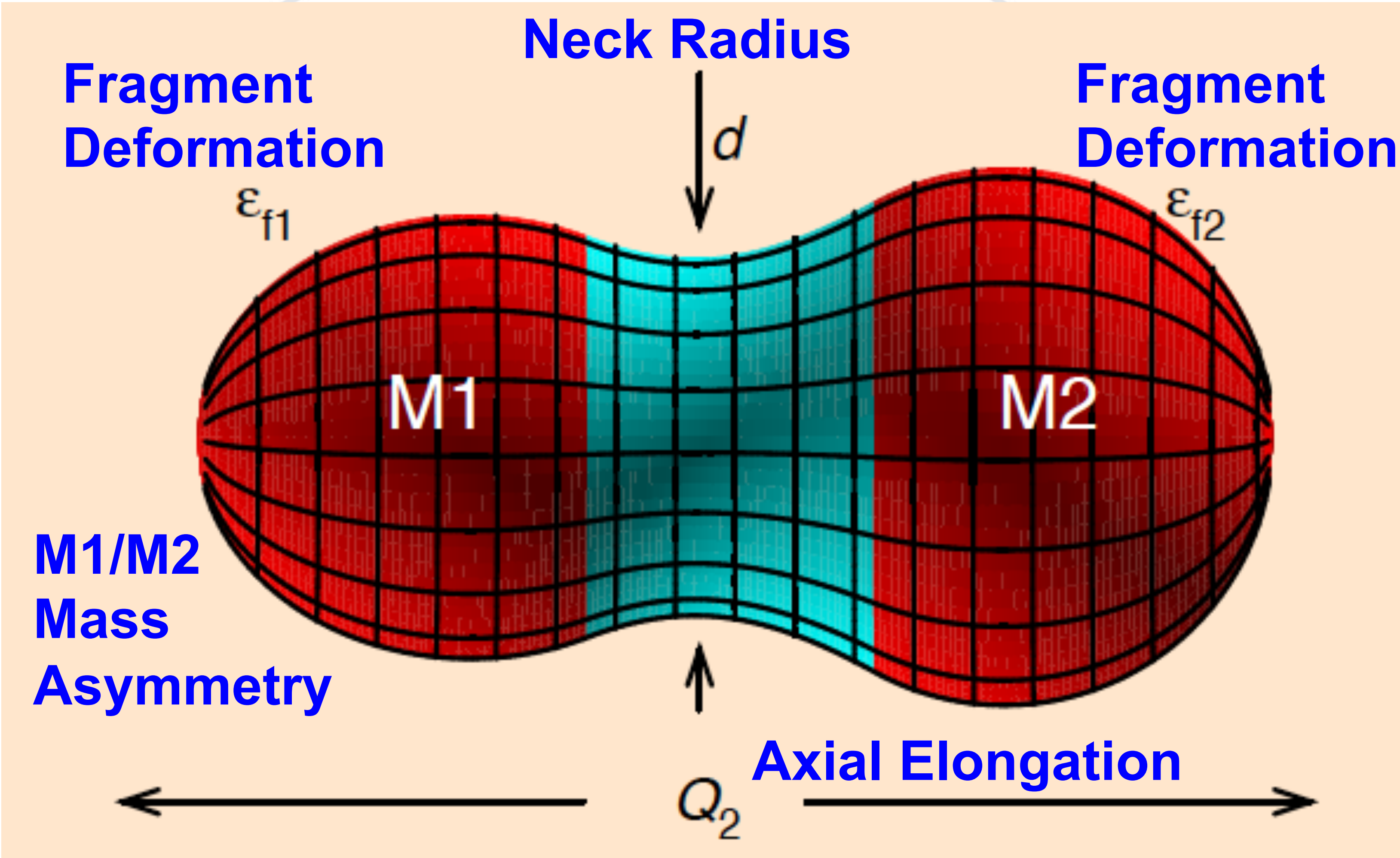
In memoriam Ray Nix (1938-2008)

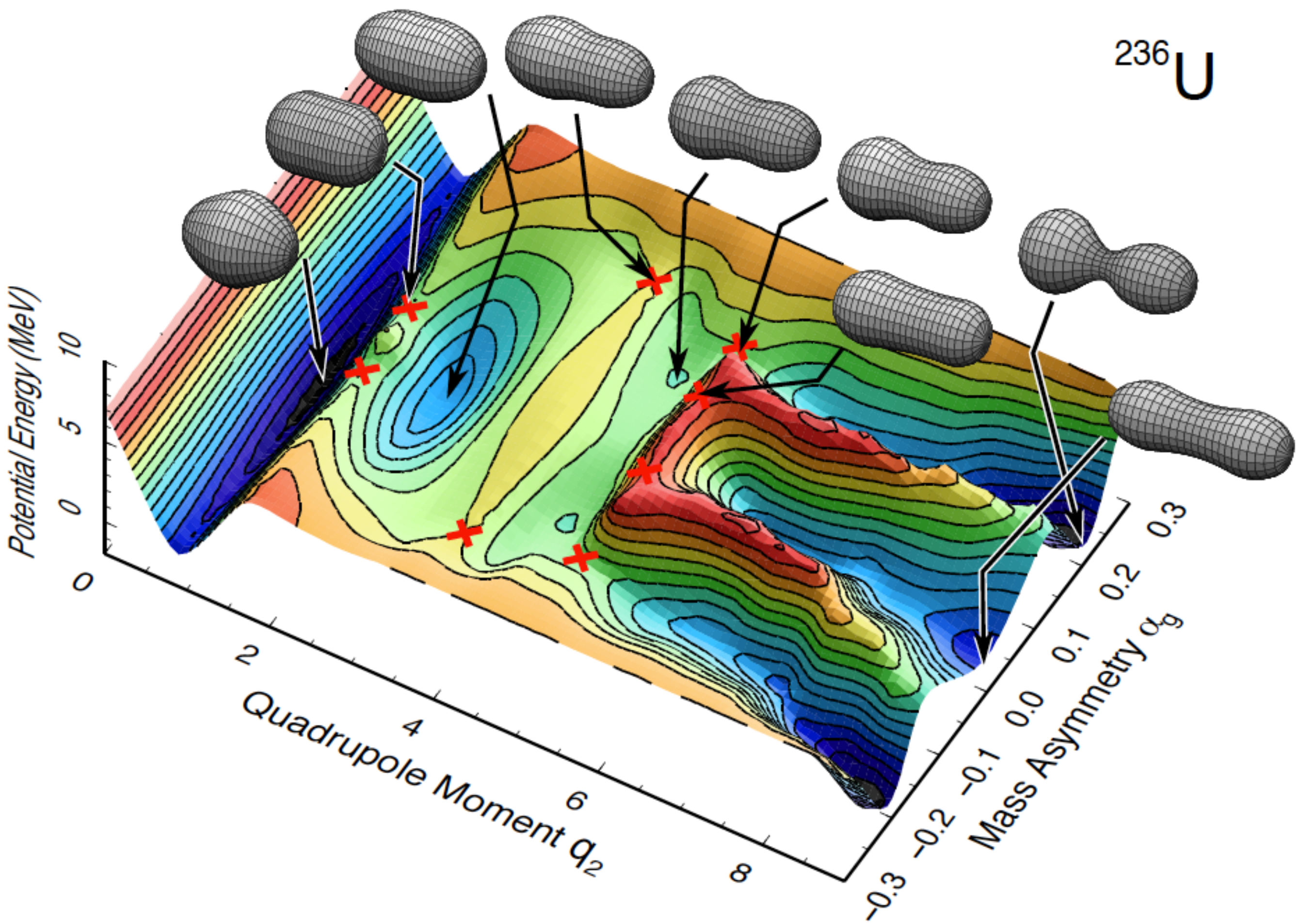
Overview
Simulating The Evolution Of Fission

- The relevant degrees of freedom for fission are the nuclear shape with its potential-energy surface
- The Macroscopic-Microscopic method is used to calculate the potential energy and its derivatives
- Thermodynamic equilibrium provides tight constraints on possible starting conditions
- Follow evolution using Monte Carlo sampling of trajectories of fissioning nuclei
- Accumulate distributions of properties of interest

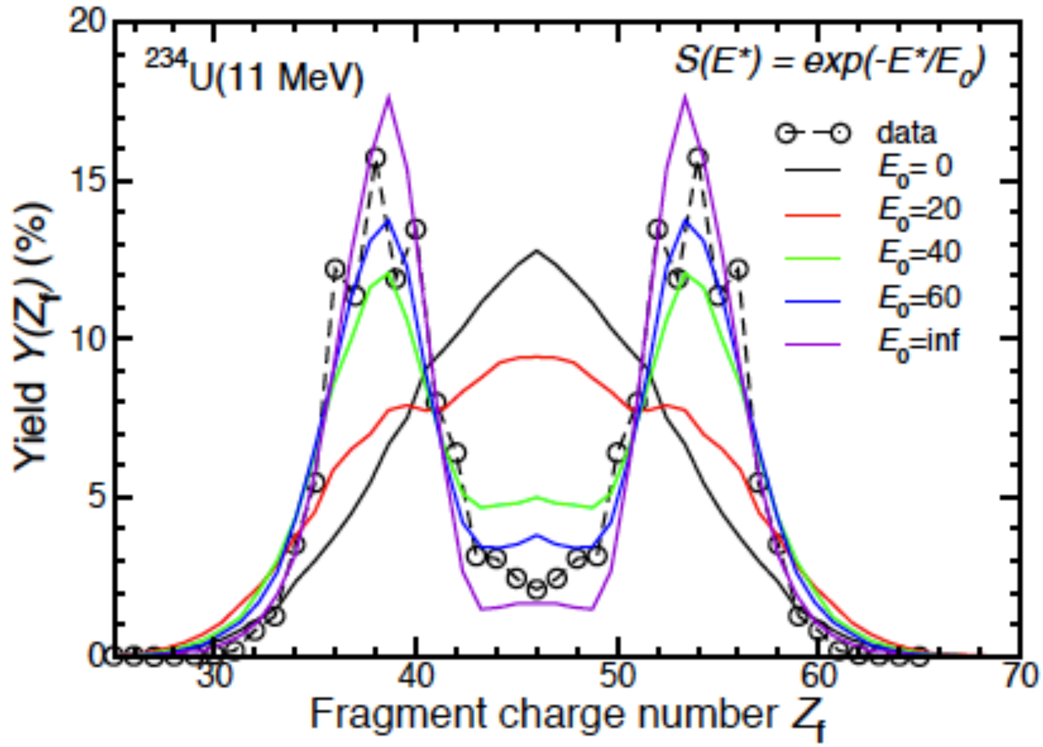
Los Alamos Global Nuclear Structure Model
Five Essential Fission Shape Coordinates

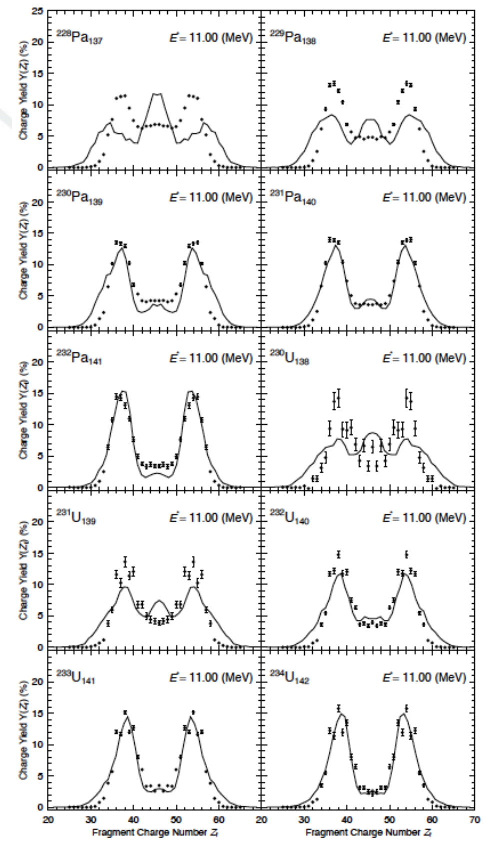


The Fission Landscape



Brownian Motion Model Producing Interesting Results





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But the limitation of time as direction without magnitude precludes predictions of fragment states, e.g. initial fragment excitation or kinetic energy.

Understanding Dynamic Evolution Requires Detailed Modeling Of Forces

- Model defines inertia and dissipation tensors which relate the kinetic energy and the energy dissipation rate to the time derivatives of the shape coordinates
  - Dissipation necessarily implies that the system encounters fluctuating forces (Fluctuation-Dissipation theorem)
- System is formally modeled using the vector Langevin equation
  - Set of five coupled nonlinear second-order stochastic differential equations

Practical Limitations

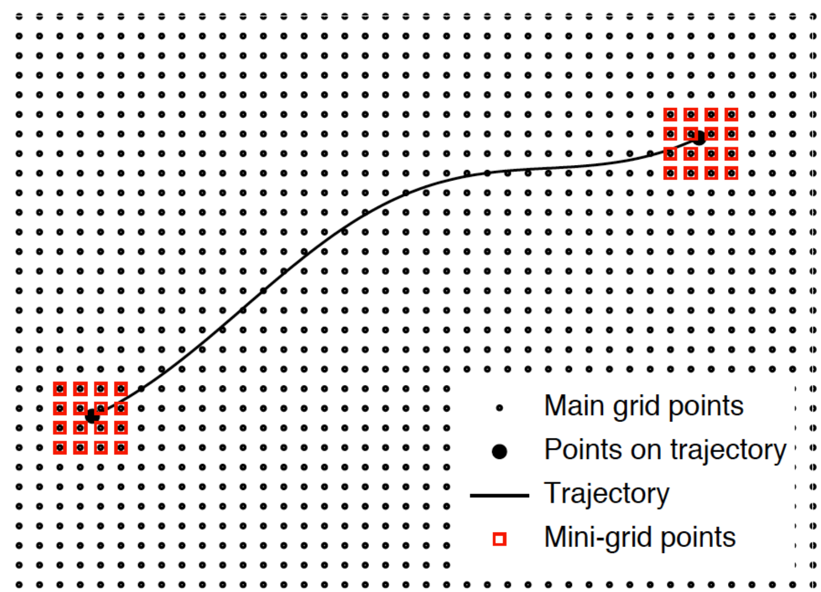
- Because of the time it takes to calculate the microscopic energy and derivatives, it is not practical to calculate the energy at each point along the fission trajectory
  - Typical calculations are based on a grid of order ~million points
- The grid must encompass the shapes the system 'wants' to encounter
  - Must be sufficiently dense so that important variations are not missed
  - Shapes should vary smoothly between adjacent grid points
- All points on the grid must describe ‘real’ shapes
- Coordinate grid has undergone multiple refinements based on feedback from the dynamical simulations
- Once refined, the coordinates encompass all expected shapes
  - U236 and Pu240 potentials have been calculated and are in active use

Iteration between dynamic implementation and two separate shape parameterizations has enhanced the robustness of each adding confidence that the potential is well understood.

Evolution of Fission Trajectories Requires Continuous Description of Force & Energy

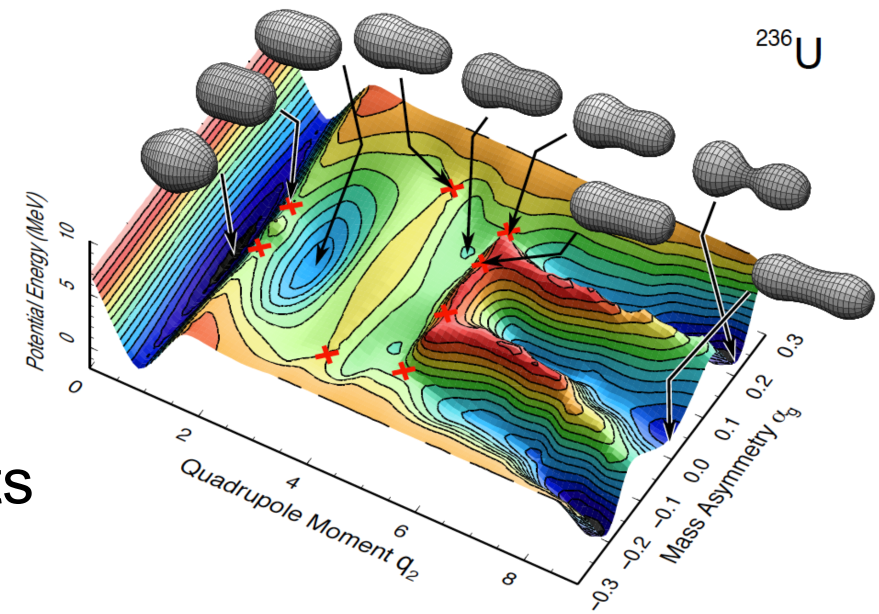
- Simple interpolation on the standard potential energy grid is insufficient
- A cubic spline approximation has been developed using an 8x8x8x8x8 ‘mini-grid’ that follows the trajectory

Cubic spline routine with microscopic corrections is ~14 times faster than original macroscopic only Langevin dynamic code.



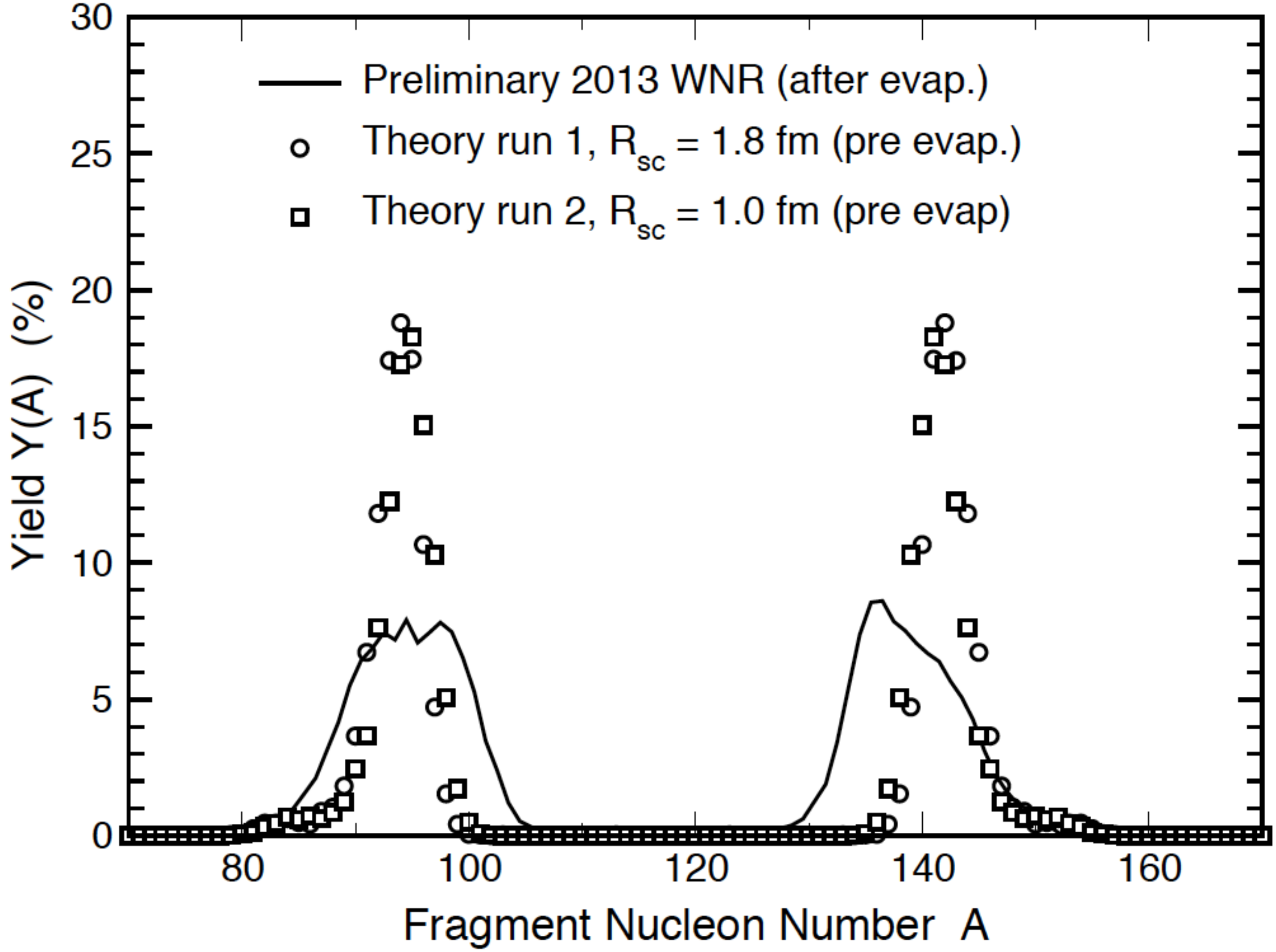
Starting Trajectories

- Now working with uranium-236 (n+U235) and plutonium-240 (n+Pu239)
- Thermodynamic equilibrium allows conditions to be described at the saddle points
- Current focus is following simulations of the normal mode (downhill) through the asymmetric valley
  - Other modes and symmetric valley will follow

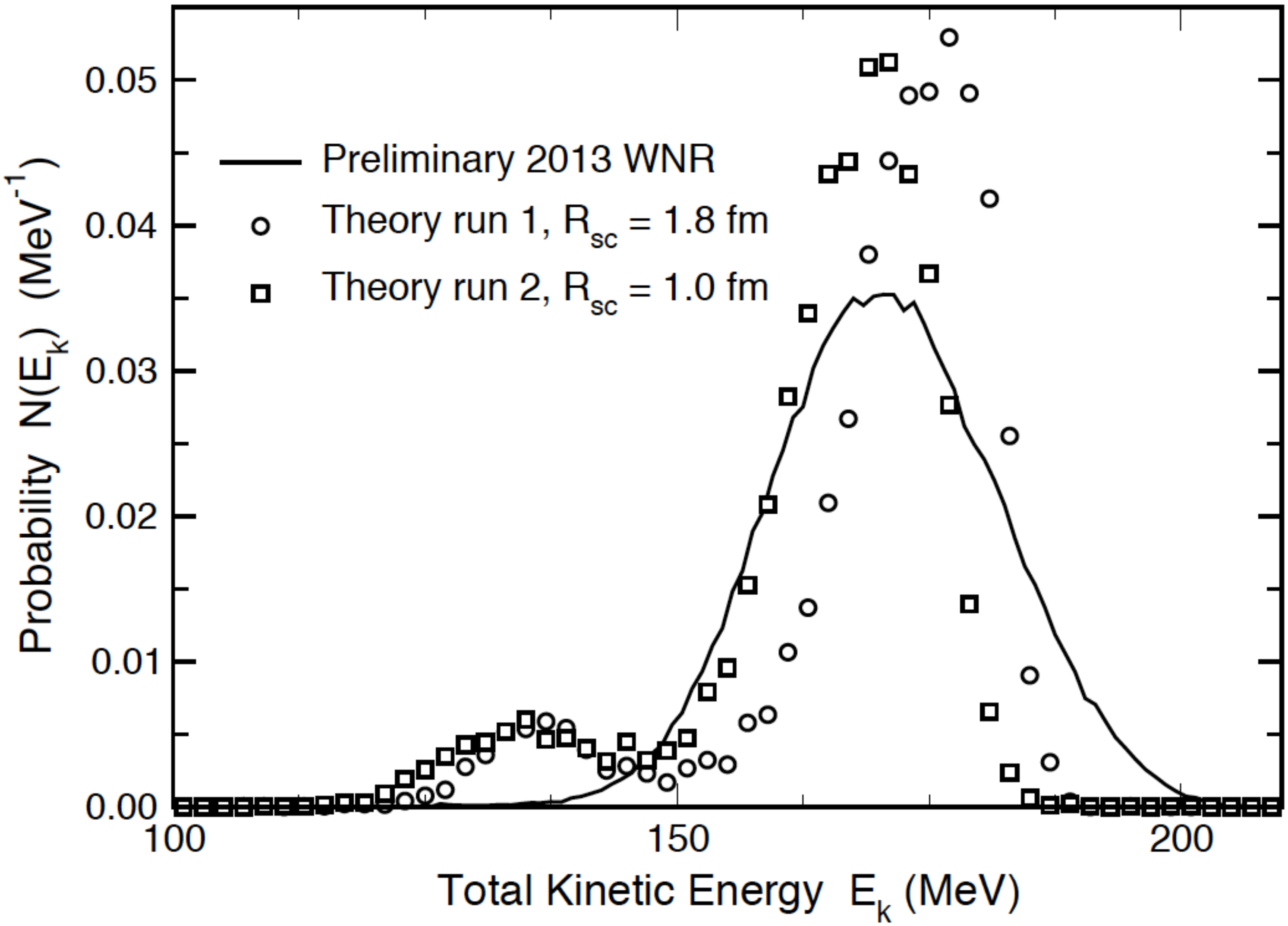


First calculations using the macroscopic-microscopic energies with full Langevin equations.

Preliminary Calculations of Fission Fragment Yields from n (0-1 MeV) on U235



Comparisons of Calculated TKE With New LANSCE Measurements



Expectations For FY2014

- Fully implement the proper thermodynamic distributions of initial conditions for the fission trajectories.
- Investigate sensitivity of the model to the incident neutron energy, the strength of dissipation, variations of the inertia model, the nuclear level density, etc.
- Locate the symmetric saddle point and investigate the properties of the separate symmetric mode of fission, including the probability of this mode as a function of incident neutron energy.

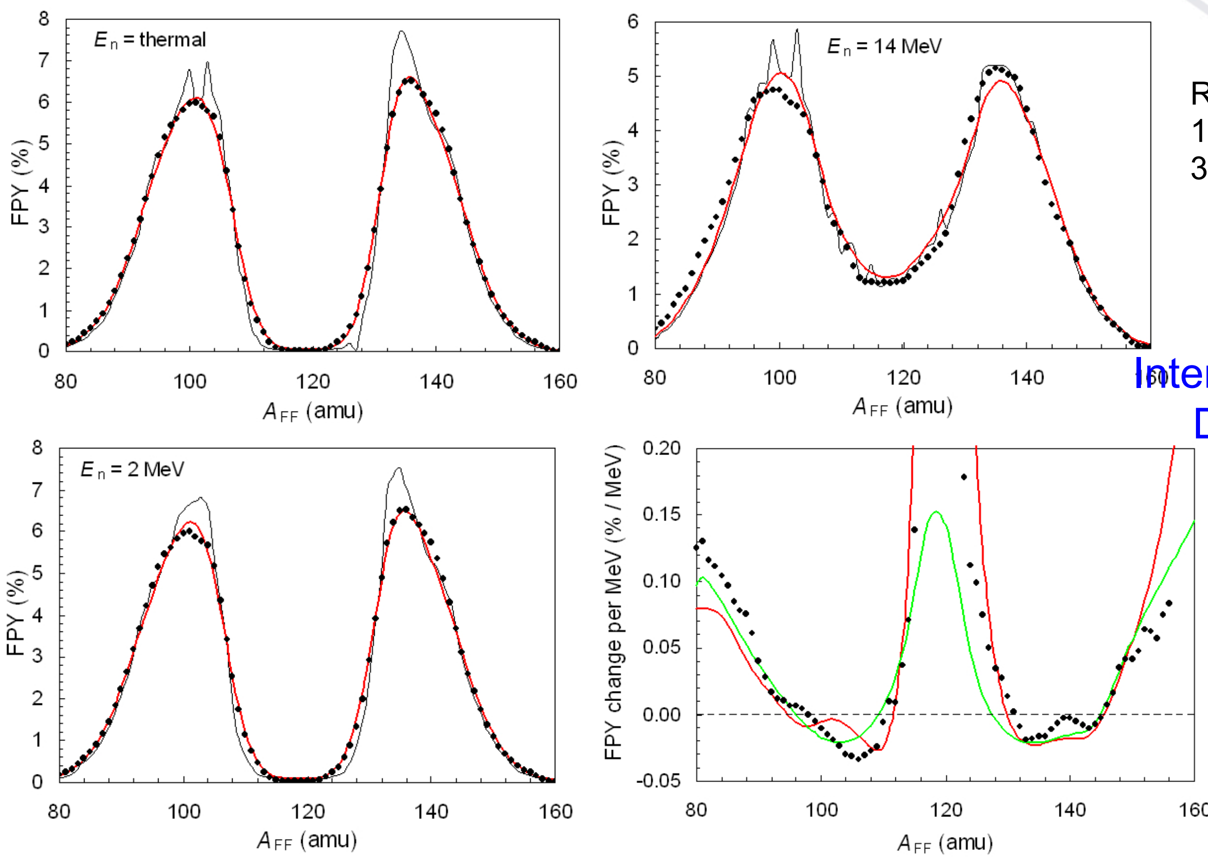
Beyond The 20120077DR…

- Study the predicted energy dependence of product A chains.
- After establishing a baseline model from U236 and Pu240 fragment data, investigate predicted distributions for other fissioning nuclides, comparing to data as available.
- Use dynamical scission states to predict distributions of excitation energy in the fragments when prompt neutrons are produced.
- Develop a more sophisticated model of post-scission dynamics to model both excitation-energy and angular-momentum distributions of fragments before prompt-neutron evaporation.

Agenda

- Overview – M. White
- Experiment – F. Tovesson
- Theory – A. Sierk
- Summary – M. White
- Discussion – All

Empirical Modeling Of Fission Fragment Energy Dependent Yields



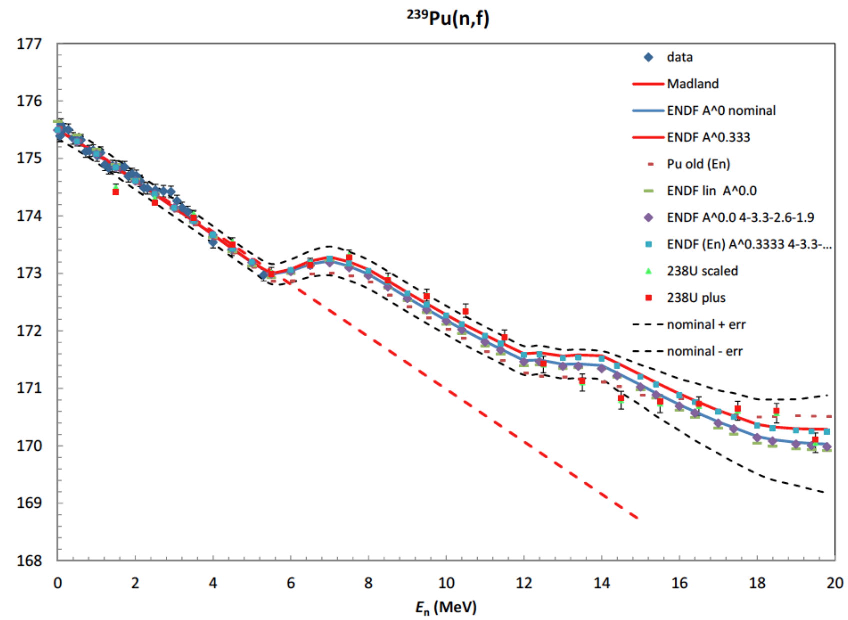
Resolution
1 AMU (black)
3 AMU (red)

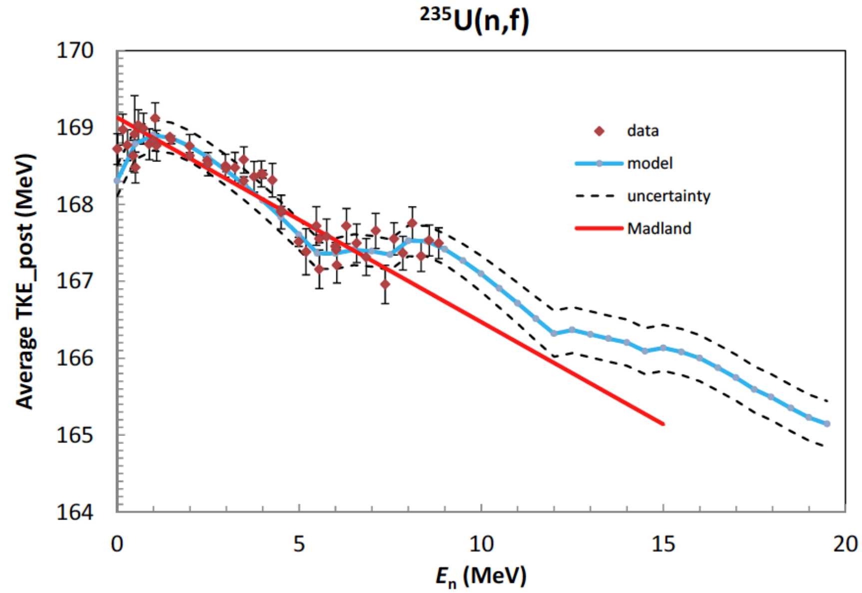
Refinements presented at the International Conference on Nuclear Data for Science and Technology (LA-UR-13-21423).

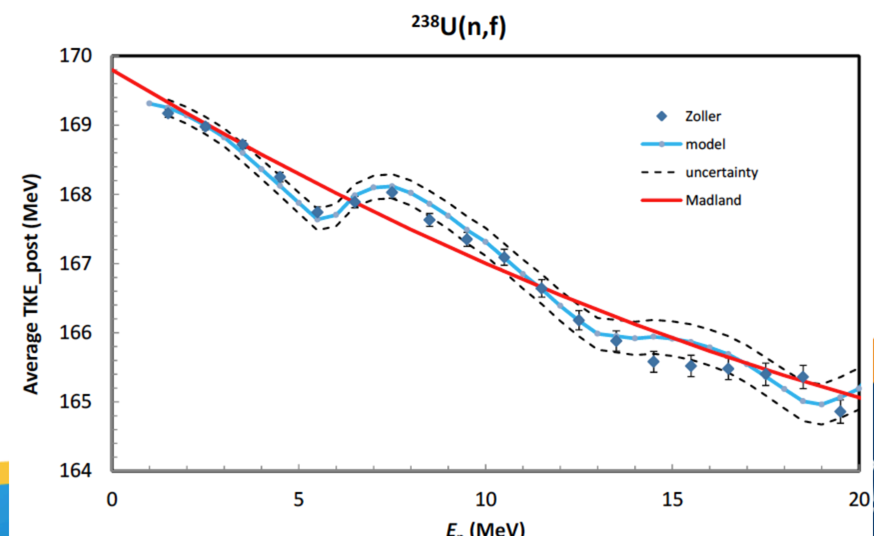
Model calculation (circles)
0 to 2 MeV (red)
0 to 0.5 MeV (green)

John P. Lestone, "Energy Dependence of Plutonium Average Fragment Total Kinetic Energies" Nuclear Data Sheets, Volume 112, p. 3120 (2011) now available as a tool for energy-dependent yield evaluation.

Empirical Modeling Of Fission Fragment Total Kinetic Energy (TKE)



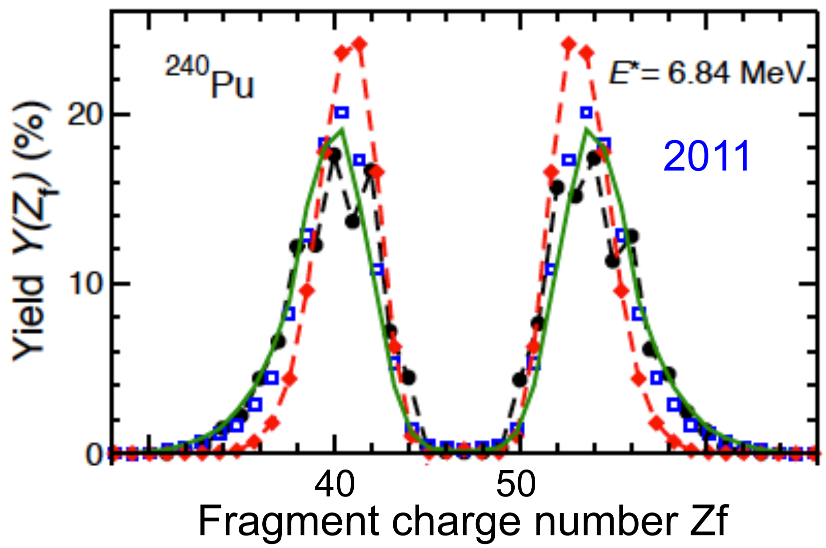


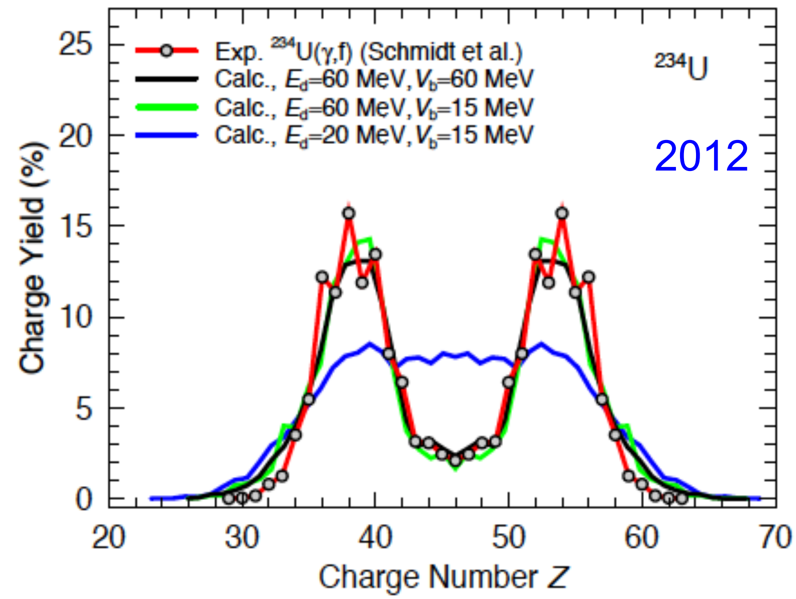


TKE empirical evaluations presented at the International Conference on Nuclear Data for Science and Technology (LA-UR-13-21423) and submitted to Nuclear Data Sheets (LA-UR-13-21567) John P. Lestone and Terrance T. Strother, "Energy Dependence of Plutonium Average Fragment Total Kinetic Energies."

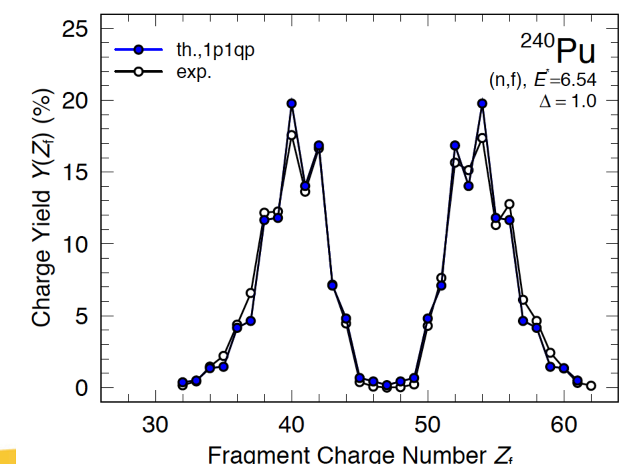
Brownian Motion LAGNS Model

Los Alamos NATIONAL LABORATORY EST. 1943





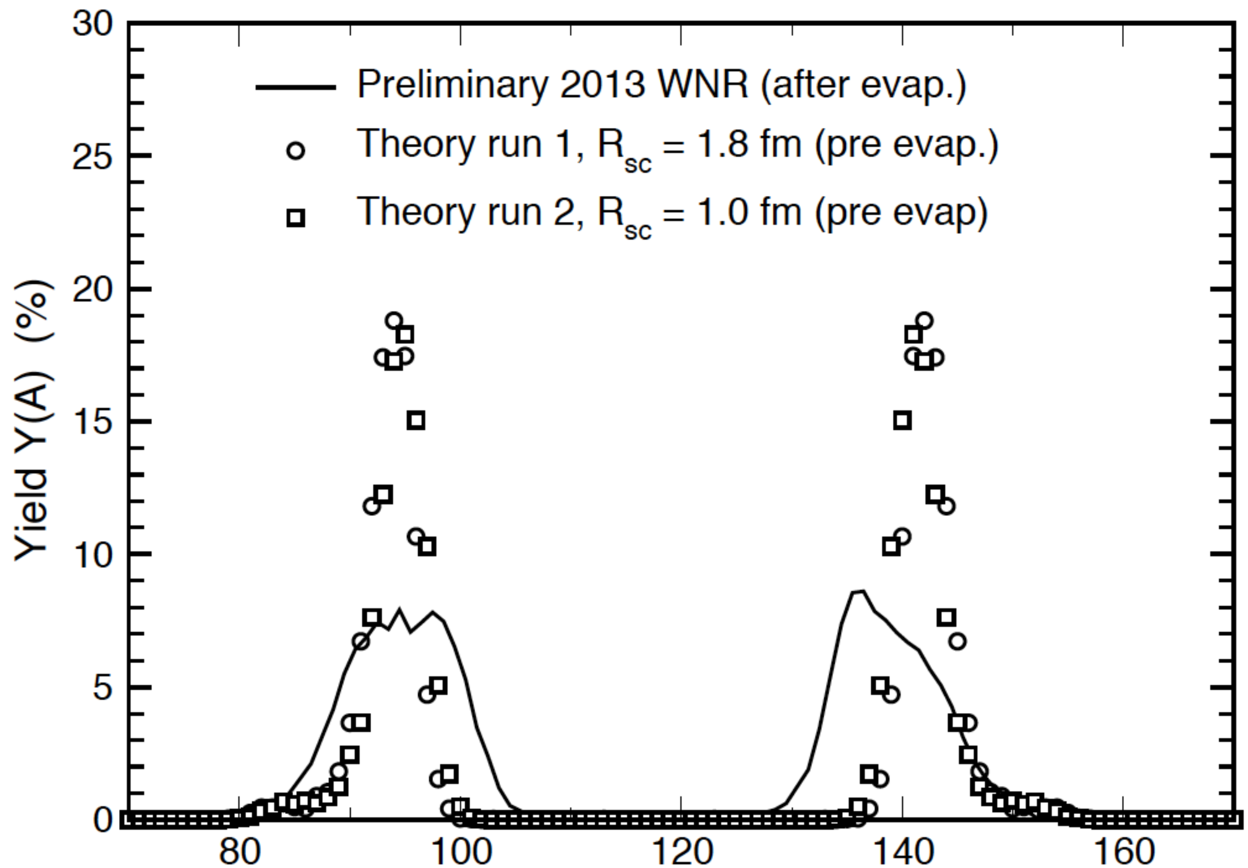
Continued refinements in the Brownian motion model are leading the way forward with concepts that will migrate to the Langevin model.



2013

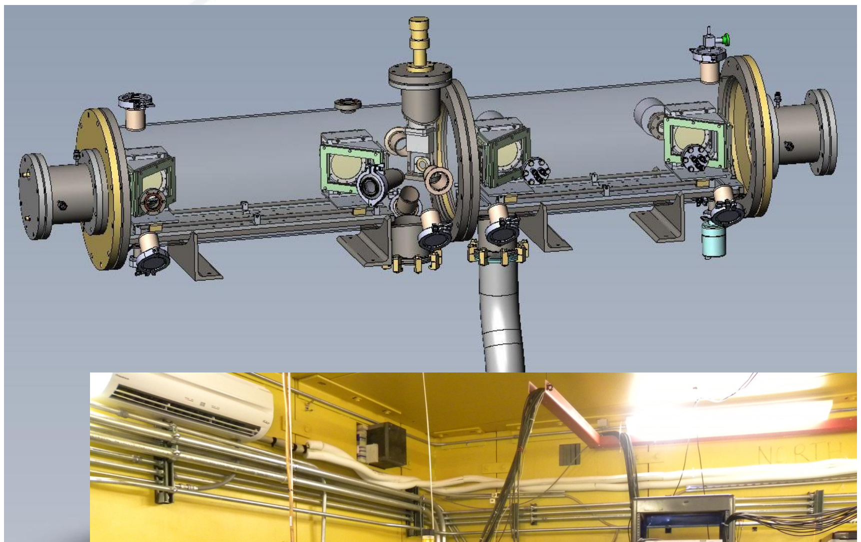
Fulfilling The Promise Of A Rich Historic Legacy – LAGNS Langevin Predictions

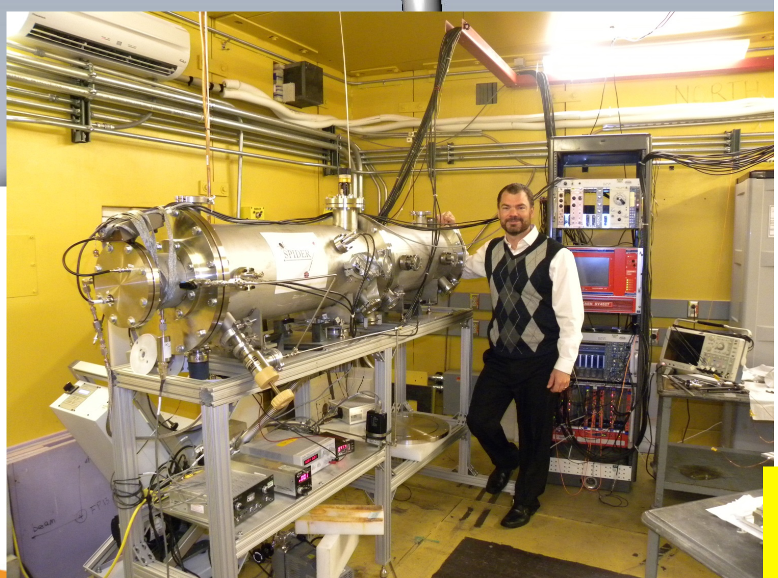
Los Alamos NATIONAL LABORATORY EST. 1943

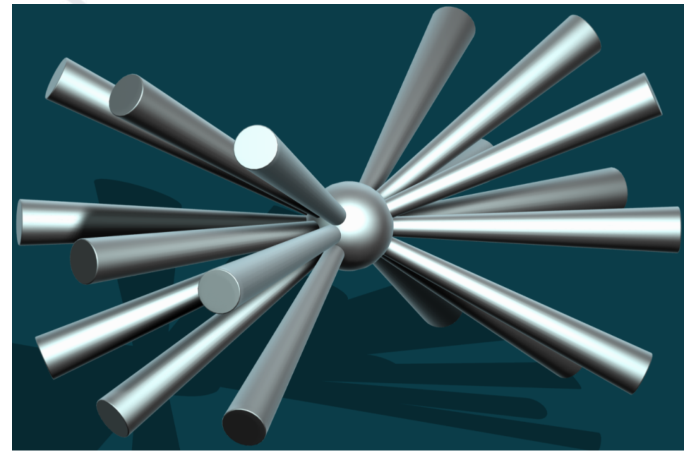


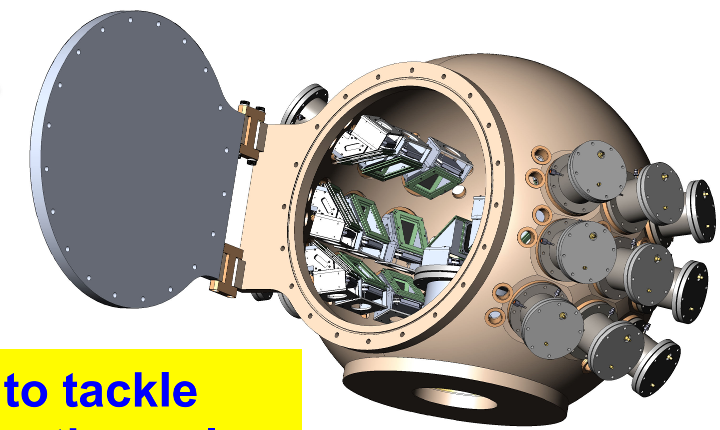
Making strides towards a truly predictive fission-fragment model.

From Conception
To Proof Of Concept
Squarely Aimed At Our Future



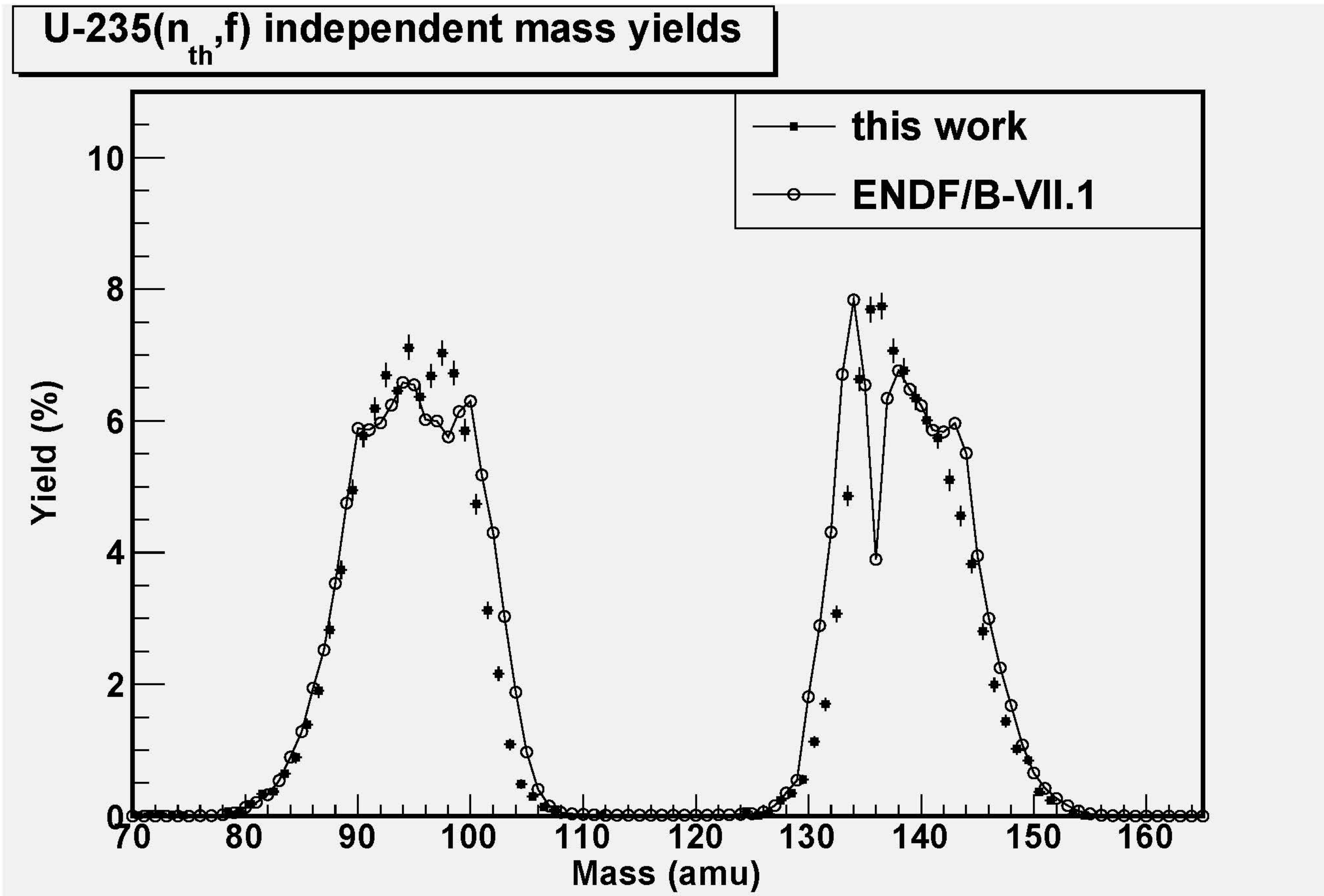






Ready to tackle programmatic goals.

First Neutron Induced Fission Fragment Measurements For SPIDER



Conclusions

- We will take high-precision californium-252 fission-fragment yield data that will provide proof-of-capability for the dual-arm instrument
- High-precision data for thermal/epithermal neutron induced fission can be made over the coming years
- Designs, and the capability to execute them, are in hand for instruments capable of making measurements for fast neutrons and for fragments in coincidence with particles
- Evaluation tools have been established to incorporate these data into standard libraries
- Advanced theory is ready to be mined for insights that will help evolve our understanding of fission

Agenda

- Overview – M. White
- Experiment – F. Tovesson
- Theory – A. Sierk
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- Discussion – All

The SPIDER Collaboration

SPIDER

- **Los Alamos National Laboratory (LANL)**
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- **Colorado School of Mines (CSM)**
  Uwe Greife, Bill Moore, Dan Shields

- **Lawrence Livermore National Laboratory (LLNL)**
  Lucas Snyder

- **Lawrence Berkeley Laboratory (LBL)**
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EST. 1943

UNM

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1874
COLORADO

LAWRENCE LIVERMORE NATIONAL LABORATORY

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

Publications

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PRC_V88_e064606-edep-ff-yields.pdf
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